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MECHANISMS OF MECHANICAL OIL EXPRESSION FROM RAPESEED AND CASHEW.

A Thesis submitted for the fulfilment of the degree of Doctor of Philosophy by:

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ABSTRACT.

The conventional theory of oil expression from vegetable oilseeds suggests that before substantial oil expression can occur, the oilseed cellwalls have to be ruptured by a combination of physical (crushing) and thermal (cooking) pre-treatments. Results from oil expression tests using rapeseed and cashew on the Instron Universal Testing Machine have suggested an alternative mechanism in which up to 80% oil is expressed through a porous cellular microstructure under pressure without cellwall rupture and at ambient temperature. The porous nature of the cellwalls has been confirmed by transmission electron microscopy. The cellwall pores (plasmodesmata) were of diameter 0.87 and 0.126 μm and average porosity of 0.093 and 0.171% of the cellwall surface area for rapeseed and cashew respectively.

The oil expression process has been succesfully described by a mathematical model based on three fundamental equations: a modified form of Terzaghi's equation for the consolidation of saturated soils, to describe the behaviour of the consolidating oilseed cake; the Hagen Poiseulle equation for flow of fluids in pipes, to describe the flow of oil through the pores on the cellwall; and Darcy's law of flow of fluids through porous media to describe the flow of oil through the intra-kernel voids. The model has

been succesfully applied to experimental data which has revealed that the flow of oil across cellwalls in the seed kernel was the rate determining step. In addition the model was also used to analyse the performance of hydraulic and screw expellers.

The study has suggested that the design of both hydraulic and screw expellers could be improved by incorporating an undrained compression pre-treatment to rupture cellwalls, and by reducing the drainage area to 0.5% - 1.5%. Furthermore, improved strategies for oil expression have been suggested in two cases. (a) For mechanical expression followed by solvent extraction it is proposed that the physical (pre-crushing) and thermal (cooking) pre-treatments are not required (b) where mechanical expression is the sole process, the pre-crushing pre-treatment should be replaced by an undrained compression pre-treatment.

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		Basic unit
A_c	- *Cylinder area*	m
A_d	- *drainage area*	%
H	- *maximum initial of path*	m
k	- *coefficient of permeability*	m/s
L_p	- *hydraulic conductivity of plasmodesmata*	m/s
Q_t	- *oil expressed to time t*	ml or %
R	- *Rate of loading*	kPa/s
t	- *time*	s
T	- *temperature*	^oC
u	- *Intra-kernel pore pressure*	Pa
$\frac{\partial q}{\partial t}$	- *rate of oil expressed*	m^3/s
ρ	- *density*	kg/m^3
σ_i	- *Kernel pressure*	Pa
σ_t	- *Total Applied Pressure*	Pa
ν	- *Coefficient of viscosity*	Poise

CHAPTER 1 INTRODUCTION.

1.1. INTRODUCTION.

Vegetable oils are used extensively in the food industry (for the manufacture of such items as salad oil and margarine) and in chemical industries (as a raw material in the manufacture of soap and lubrication products) (Swern, 1964). The residue left after mechanical or chemical extraction of the oil from vegetable oilseeds is a protein rich cake which is used for the manufacture of animal feeds and in some cases textured protein products for human consumption (Brian, 1976).

The separation of the oil from the oilseeds is achieved by mechanical expression or solvent extraction or a combination of both. Mechanical expression of oil from vegetable oilseeds is the most widely used method for oil extraction. A survey of the literature in the field of oil extraction reveals a distinct lack of understanding of the mechanical oil expression process (Norris, 1964; Ward, 1976).

The general objective of this project is to investigate the mechanisms by which oil is expressed from vegetable oilseeds by mechanical means. The elucidation of the fundamental mechanisms allied with a knowledge of the physical and thermal parameters affecting the process should enable the design of more effective oil expression equipment.

1.2. SELECTION OF OILSEEDS

There are over 100 seeds which contain oil and could be used as a source of oil (Vaughn, 1972). The major oilseeds (Mielke, 1976) are:

(a) Annual crops: such a soyabeans, cottonseed, sunflower, rapeseed and groundnuts (peanuts).
(b) Tree nuts: such as palm kernels and copra.

This study will be restricted to two oilseeds:-
(a) Rapeseed:- an annual crop grown in temperate climates which has a high potential for countries like Ireland which import nearly all their oilseed requirements (O'Farrell, 1976).
(b) Cashew-kernels: - a tropical tree nut which has a high potential as a source of oil due to the ability of the cashew tree to be used as a means of controlling soil erosion in the countries where it is grown (Woodroof, 1969; Russell, 1969).

1.3. CLASSIFICATION OF OILSEEDS

Oilseeds are classified according to the amount of oil they contain. There are two main types:-

(a) High oil content seeds (over 25% oil content by weight).

Rapeseed	42 - 47% oil	(Appelquist and Ohlson,1972)
Cashew Kernels	38 - 43% oil	(Mohapatra *et al*,1972)
Copra	65% oil	(Swern,1964)
Palm Kernels	48% oil	(Swern,1964)
Groundnuts	50% oil	(Swern,1964)

(b) Low oil content seeds(under 25% oil content by weight).

Soyabeans	15% oil	(Swern, 1964)
Cottonseed	19% oil	(Swern, 1964)

The amount of oil present determines the method which will be used for extraction of the oil. Mechanical expression is normally used for high oil content seeds while solvent extraction is normally used for low oil content seeds. (Norris, 1964).

1.4 OIL EXTRACTION METHODS

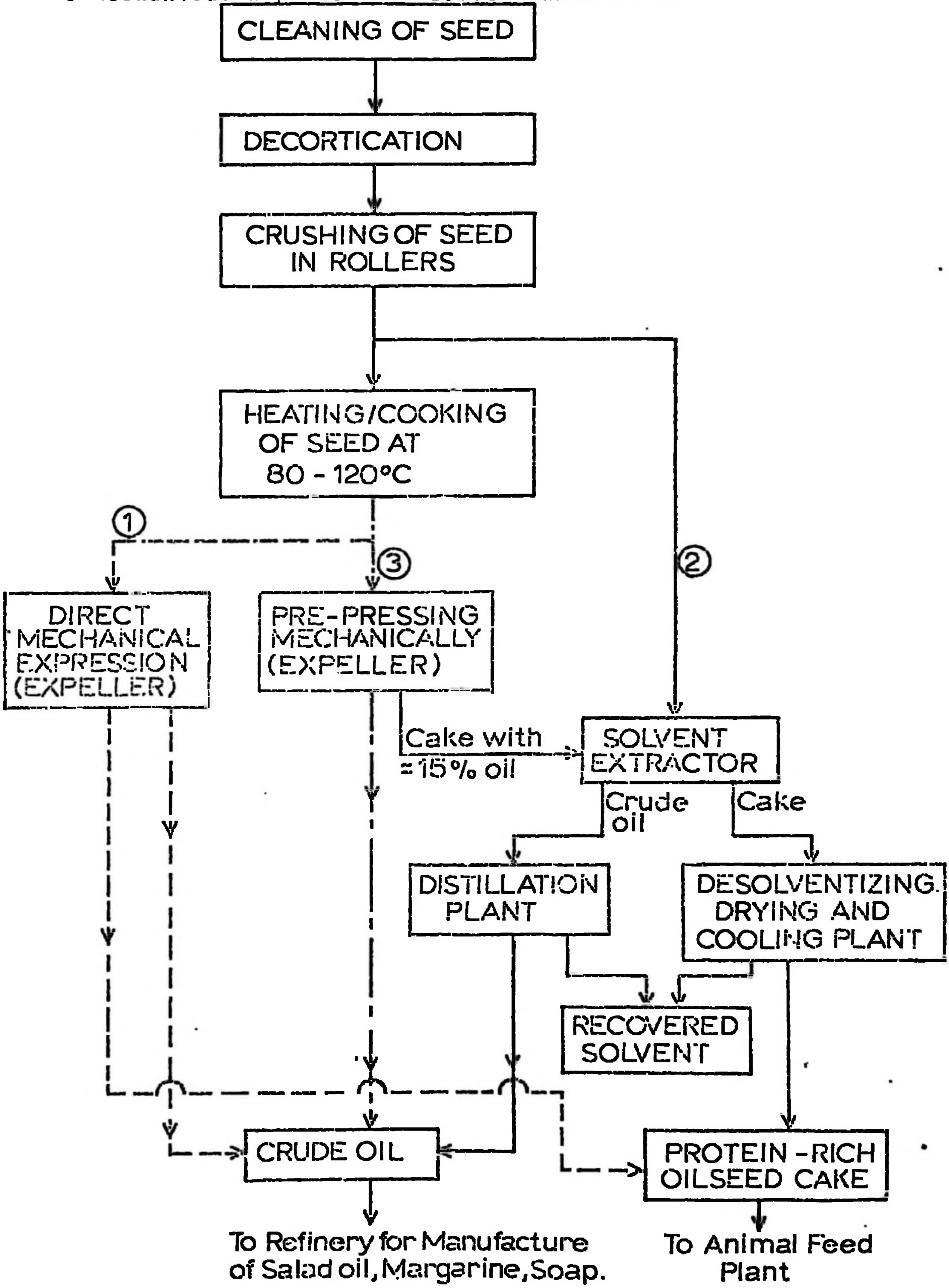
1.4.1 INTRODUCTION.

A typical oil expression flow chart is shown in Fig. 1. The following stages are involved:

(a) Seed preparation:- This involves the cleaning of the seeds to remove any dirt, stones, and metal pieces. Cleaning is followed by decortication (removal of the hull) in some seeds as both the meal and oil quality are higher in decorticated seeds. Cashew nuts are usually decorticated before oil extraction whereas small seeds such as rapeseed (≈ 2 mm diameter) are difficult to decorticate and oil extraction is usually done without decortication.

(b) Crushing of the seeds:- The extraction of oil from vegetable oilseeds either by mechanical means or by solvents is facilitated by reduction of the seeds to smaller particles. Opinion is divided in the oil extraction industry whether grinding or rolling of the seeds disrupts and ruptures a larger proportion of the oil bearing cells in the seeds (Norris, 1964). The assumption of extensive cell wall rupture has in the past been based chiefly (Norris, 1964) upon the fact that rolled seed flakes yield a large fraction of "easily extractable" oil upon treatment with solvents (which was assumed

FIG. 1: FLOW CHART OF OIL EXPRESSION METHODS.
1 - Direct mechanical Expression, 2 - Solvent Extraction
3 Mechanical Expression + Solvent Extraction.



to come from ruptured cells) and a small fraction (10 - 30%) of oil that is extracted with much greater difficulty (assumed to come from unruptured cells) (Osburn and Katz, 1944).

(c) Cooking of the oilseeds:- The cooking of the seeds involves heating them at temperatures of 80°C - 100°C for about 30 to 60 minutes depending on the type of seeds. (Ward, 1976; Appelquist and Ohlson, 1972; Dunning 1956). Woolrich and Carpenter (1935) could observe little disruption of the cell walls after rolling, and further Ward (1976) Appelquist and Ohlson (1972) have claimed that many oilseed cells remain intact even after the most careful reduction, and these walls are made permeable to the oil by the action of heat during the cooking operation.

In contrast however, Norris (1964) claims that the primary objectives of the cooking operation are:
(i) Coagulation of the proteins in the oilseed cells causing coalescence of oil droplets and making the seed permeable to oil flow.

(ii) Decrease the affinity of the oil to the solid surfaces of the seed so that the best possible yield of oil may be obtained when the seeds are subsequently pressed.

In Chapter 5 we shall discuss these opposing view points as they relate to the mechanisms of oil expression in greater detail.

(d) Extraction Methods:

There are three methods which are used for extraction of oil from vegetable oilseeds:

(i) Mechanical expression.
(ii) Solvent extraction.
(iii) Mechanical expression followed by solvent extraction.

The selection of the method to be used is dependent on:-

(i) Economics:- capital costs for a solvent extraction plant are quite high.
(ii) Oil content of the seeds:- solvent extraction is efficient for seeds of low oil content.

1.4.2. MECHANICAL OIL EXPRESSION.

This is the oldest and most widely used method of oil expression in which the objective is to reduce the oil content of the seeds to 5 - 9% (Norris, 1964; Ward, 1976).

The process essentially involves enclosing the pre-crushed and cooked oilseed cake in a suitable filtering or retaining envelope and applying external compressive pressure under conditions such that the oil is forced to the outside where it can be removed. The pressing conditions depend on the type of machine (expeller) being used. There are three main types of expellers:-

(a) Hydraulic Expellers:- This is a batch process in which the presses are designed to exert a uniaxial pressure of up to 31 MPa with an average pressure on the oilseed cake enclosed in a filter cloth of 12 MPa (Norris 1964; Appelquist and Ohlson, 1972). The pressure on the cake is built up at a rate of about 60 kPa/s (500 psi/min) until the maximum pressure and held there for about 30 minutes.

(b) Screw Expeller:- This is a continuous expeller consisting of a main shaft with worms on it with the diameter increasing towards the discharge end and contained inside a constant diameter pressure chamber. The main purpose of the shaft is to exert an increasing pressure on the cake and at the same time convey it forward through the pressure chamber. The lower half of the pressure chamber is made up of rectangular bars (≈ 12.7 mm width) separated by spacing clips which provide spaces varying from 0.25 mm to 0.76 mm depending on the type of seeds being pressed - (for small seeds like cottonseed, rapeseed, the spacing is 0.25 mm whereas for larger seeds - copra the spacing is 0.76 mm) (Norris,1964). This acts as a coarse filter permitting the drainage of the expressed oil and keeps the cake within the drainage barrell. The shaft generates two types of forces - a compressive radial force which is used for expressing the oil and an axial force which is used to convey the seedmass forward and overcome the frictional forces between the cake and shaft. A considerable amount of heat is generated and normally the shaft has to be cooled. The magnitude of radial forces is about 230 MPa but the axial forces have not been measured. (Norris ,1964; Appelquist and Ohlson, 1972; Ward, 1976).

(c) Rotopress:-

This is a new type of continuous expeller which has come into the market in the last 3 years. An eccentrically mounted fluted roller is used to build the pressure on the cake instead of a shaft and worms as in the screw expeller. Data on the performance of this new type of press is not yet available. (Tindale and Hill-Haas, 1976).

1.4.3. SOLVENT EXTRACTION.

This method is most advantageous in the recovery of oil from low oil content seeds such as soyabeans and cottonseed or high oil content seeds which have been pre-pressed by mechanical presses and their oil content reduced to about 15%. The equipment and principles of operation used in this method have been described in detail by among others Norris (1964); Stein and Glaser (1976); and Bernadini (1976).

1.4.4. MECHANICAL EXPRESSION FOLLOWED BY SOLVENT EXTRACTION.

This method is most suitable for seeds of high oil content (over 25% oil content). The crushed and cooked seeds are pre-pressed by the conventional machinery to reduce the oil content to 10 - 15%. Solvent extractors are used to extract the remaining oil (Norris 1964; Appelquist and Ohlson, 1972).

1.4.5. CONCLUSION.

For high oil content seeds such as cashew and rapeseed direct solvent extraction is not suitable. The oil has therefore to be extracted by either direct mechanical expression or by mechanical expression followed by solvent extraction. The solvent extraction process has received detailed studies by among others Boucher *et al* 1942; Osburn and Katz, 1944; Othmer and Agarwal, 1955; whereas the mechanical expression process is not well understood fundamentally.

1.5 GENERAL STATEMENT OF THE PROBLEM.

The expression of oil from vegetable oilseeds by mechanical means is a widely used process in the vegetable oil industry. The design of machinery used for the expression of oil has evolved more as an art than a science (Ward 1976; Norris 1964; French 1956). The effect of such pretreatment processes as pre-crushing and cooking are not well understood. The energy requirements of existing machines in the market are high (Tindale and Hill-Haas, 1976; Appelquist and Ohlson, 1972). It is now likely that increasing interest will be shown by manufacturers in more energy efficient machines.

A need exists for a fundamental study of the process of expression of oil by mechanical means from vegetable oilseeds. It is proposed to carry out such a study on representative high oil content seeds - cashew - a tropical tree nut and rapeseed - a temperate annual crop.

This project will elucidate the mechanisms and controlling parameters of the mechanical oil expression process. The elucidation of the fundamental expression mechanisms allied with a knowledge of the physical and thermal parameters affecting the process should enable the design of more effective oil expression equipment.

CHAPTER 2. LITERATURE REVIEW.

2.1. MICROSTRUCTURE OF OILSEEDS.

Oilseeds are composed of cotyledon(s) inside a hull or seedcoat. Most of the oil is in the cotyledon(s) (kernel). In some seeds such as cashew, peanuts, cottonseed the seeds are dehulled before oil extraction whereas in small seeds such as rapeseed there is no dehulling.

The kernel is composed of microscopic cells (25 - 60 µm in diameter). The oil in these cells is in form of ultramicroscopic droplets of 0.2 - 0.5 µm diameter (Fig. 2). With the oil in the seed cell are other constitutents like proteins, nucleus and carbohydrates. There are two conflicting models of the cell structure (cf. Fig. 3) In the first model which is used in the oil extraction literature (Norris, 1964; Smith and Circle, 1972; Ward, 1976) the cell wall is impermeable to oil flow and for oil expression to occur:-

(a) The cell wall has to be ruptured by a combination of mechanical and thermal forces.

(b) The oil droplets have to be coalesced into larger droplets by action of heat.

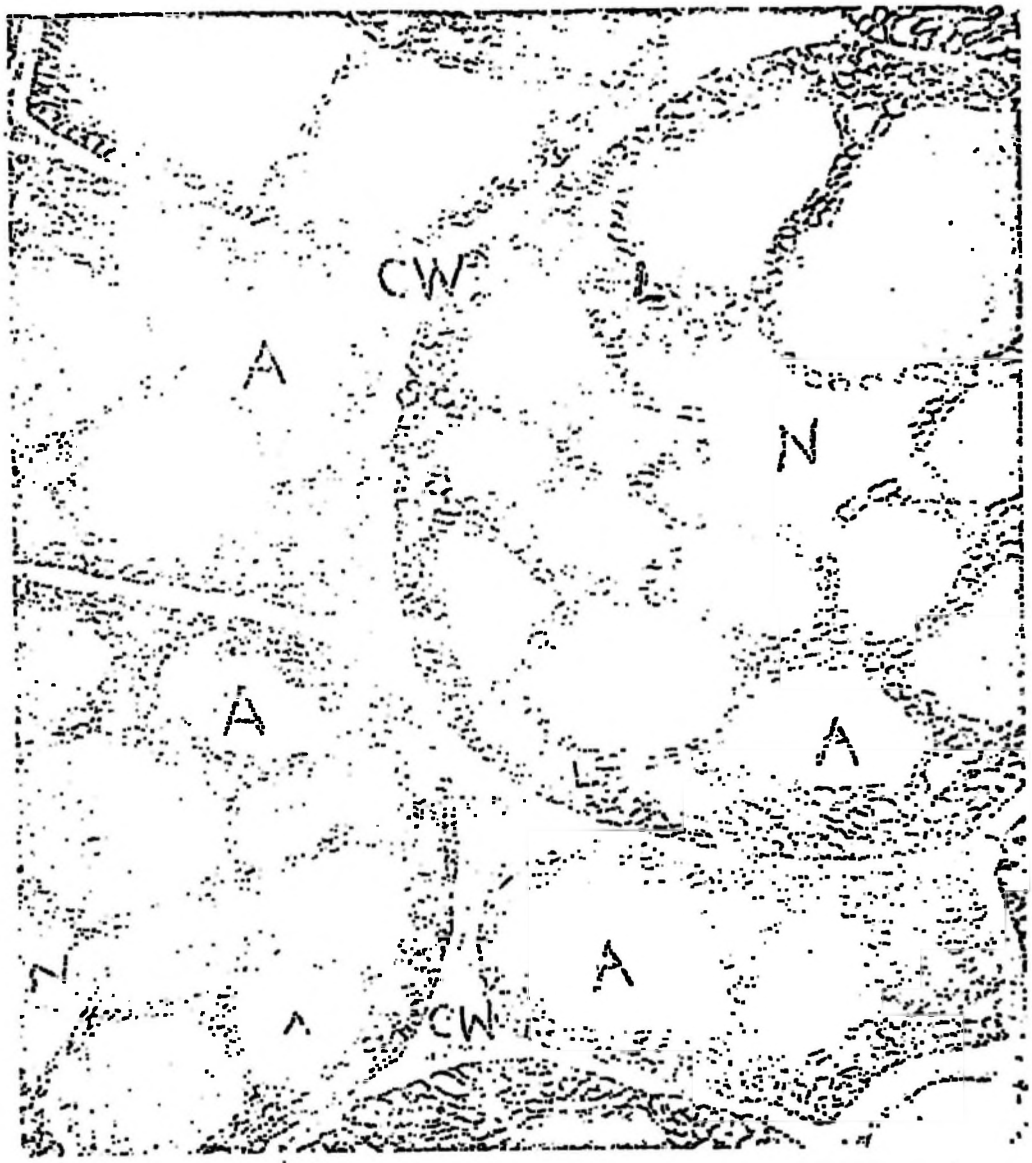


Fig. 2 Electron micrograph of oilseed rape (*Brassica napus*) (8,000 ×)
CW Cell Wall L Lipid droplets
A Aleurone grains N Nucleus

From Appelquist and Ohlson (1972)

FIG 3: MICROSTRUCTURE MODELS OF OILSEEDS.

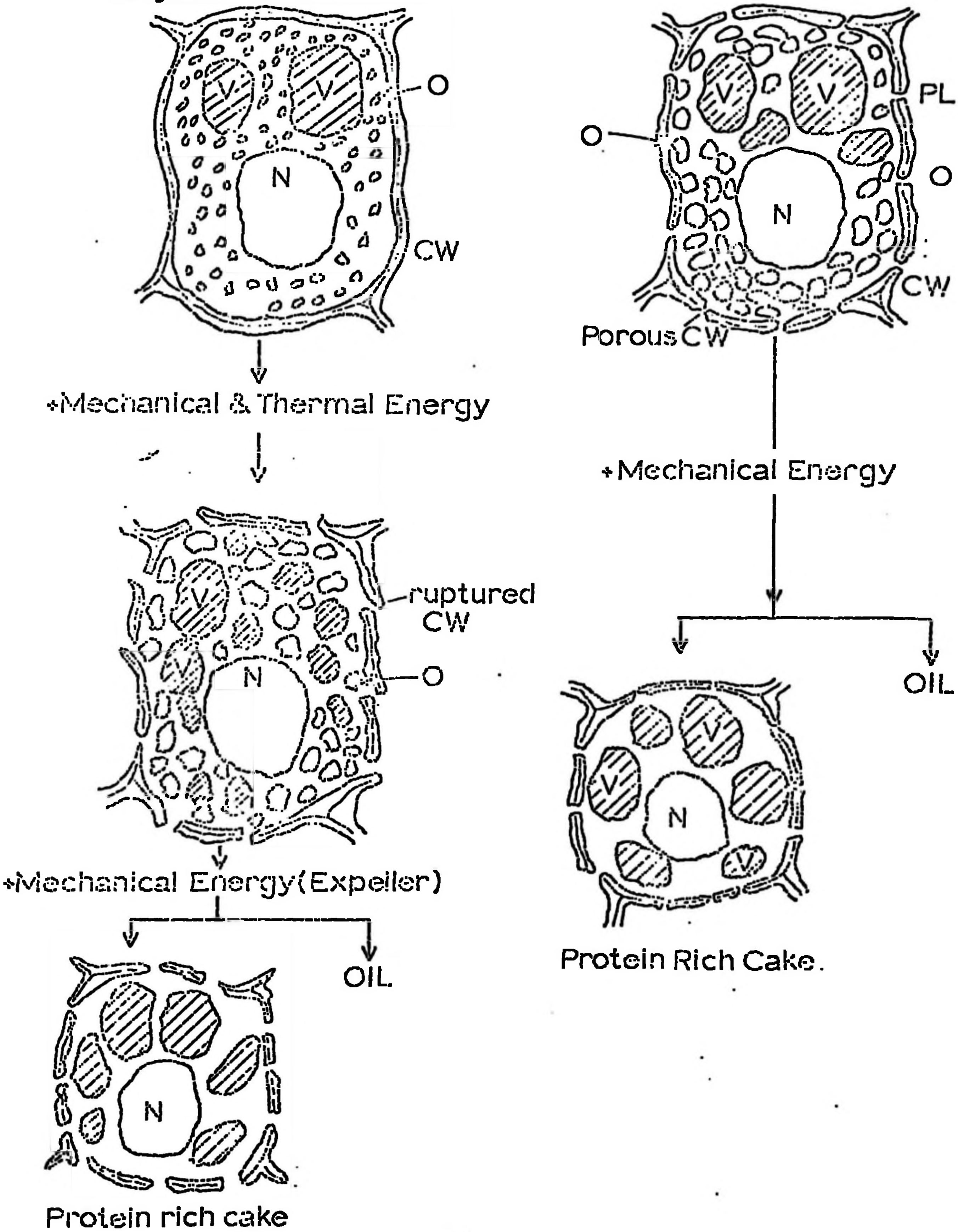
CW-Cellwall; V - Protein Vacuoles; O - oil droplets; N - Nucleus. PL - Pores on Cellwall (plasmodesmata).

MODEL 1

Cellwall rupture and protein coagulation model.

MODEL 2

Porous cellwall model.



(c) The proteins have to be coagulated by the action of heat.

After this the seeds are then sent to the mechanical expeller for oil expression. In the second model which has been suggested by plant physiologists (Diekert and Diekert, 1972, 1976; Vix *et al* 1972;) the cell wall is porous and it is suggested that oil could be expressed through these pores (plasmodesmata) on the cell wall.

2.2. EMPIRICAL EXPRESSION MODELS FOR OILSEEDS.

2.2.1. INTRODUCTION.

Norris (1964) and Ward (1976) have claimed that oil expression is a complex process and that it is not possible to develop an equation which would describe the process using basic engineering principles. Several researchers have proposed empirical equations designed to permit the calculation of the fraction of oil expressed from the seeds from data on pressing time, pressure on cake, viscosity and temperature.

2.2.2. PRESSURE - VISCOSITY - TIME MODEL.

Based upon experimental data on expression of seven oilseeds (soyabean, cottonseed, rapeseed, peanut, sesame seed, tung nut and castor bean) Koo (1942) proposed the following empirical equation:

$$(W_e / W_0) = (C P^{0.5} \; t^{0.167}) / (\nu^{z})^{0.5} \qquad (1)$$

where W_e = weight of oil expressed (dry basis) at the end of an expression test.

W_0 = original oil content of the seeds in weight (dry basis).

where P = Applied Pressure in psi up to 5000 psi (34.5 MPa)

t = Pressing time in hours (0.5h - 5h)

ν = Coefficient of Kinematic viscosity of the oil at the pressing temperature (in stokes). Temperature, T, varied from 18°C to 125°C) (ν assumed to be a function of T only).

z = exponent of viscosity factor varying from 0.167 to 0.5.

C = a constant for one type of oilseed and press being used (was 5.83×10^{-3} for rapeseed and Koo's hydraulic press).

The experimental data was obtained using a laboratory hydraulic press with 15.24 X 15.24 cm pressing surfaces between which a maximum pressure of 34.5 MPa (5000 psi) could be obtained by a hand operated oil pump. Electric hot plates were provided for heating when the temperature effect was being studied. The effects of pressure, temperature and time were tested by varying one factor at a time. The oil yield was obtained by weighing the seeds before and after pressing and getting the difference between the two. The samples were decorticated and ground to a "desirable uniform size".

Equation (1) therefore is a product of three linear equations of W_e/W_o - fraction of oil expressed aginast (i) $(t)^{0.167}$ with P and ν kept constant, (ii) $(P)^{0.5}$ with ν and t kept constant and (iii) $(1/\nu^2)^{0.5}$ with P and T kept constant. It is based on data obtained at the end of pressing and does not describe the process as a function of pressing time. It is significant however, that Koo in his model assumes that temperature affects the viscosity of the oil only, thus implying that thermal treatment does not affect cell wall rupture.

2.2.3. PRESSURE - TEMPERATURE - TIME MODEL.

Using the same procedure as Koo (1942), Baskerville et al, 1947, suggested another empirical equation to describe the expression process:-

$$W_e/W_o = 1 - ((2.48 \times 10^{18})/((t^{0.181}(460 + T)^{6.23}P^{0.452}))) \quad (2)$$

where T = Temperature in ^oF and all other parameters are as in equation 1.

The basic difference between equations(1)and(2)is that in the former temperature is assumed to affect viscosity only whereas in the latter it is not. Temperature has a greater effect on the amount of oil expressed in equation (2) compared to viscosity in equation (1) otherwise the effect of pressing time and pressure on oil expressed is similar in both equations.

2.2.4. PRESSURE - VOLUME MODEL.

Gurnham and Masson (1946) proposed a pressure - volume equation to describe the expression process using model materials simulating oilseeds such as cotton and wool impregnated with oil or water. Their equation was based on data obtained from expression tests on a hydraulic press with pressure range from 0 to 138 MPa (20,000 psi). A 28.6 mm diameter plunger/cylinder rig was attached to the press and volume changes were taken by a dial micrometer attached to the rig. Their equation was:

$$\text{Log } P = a + (b/V) \tag{3}$$

Where P = applied pressure (0 to 20,000 psi (137.9 MPa)).

V = specific volume of the sample at the end of pressing (ml/g) (1.76 - 0.701)

a and b are constants for a particular material. Equation (3) is based on data at the end of an expression test and does not consider expression as a function of time.

2.2.5. RECOMMENDATIONS FOR EFFICIENT OIL EXPRESSION.

Carter (1953) investigating factors affecting the efficiency of hydraulic expellers concluded that it was impractical to write an equation which will relate the pressing variables (pressure, temperature, time and moisture) and the residual oil content in the cake. Using his own laboratory experimental data and data from hydraulic press mills, he gave the following recommendations for efficient expression of oil from cottonseed:-

(i) There is no advantage to be gained by using pressures of more than 13.8 MPa unless the final cake thickness is more than 25.4 mm thick.

(ii) The seeds should be decorticated.

(iii) There is little advantage to be gained in pressing longer than 35 minutes.

(iv) Cooking and pressing should be done at about 99^{o}C (210^{o}F).

Similar recommendations were made by Hickox (1954). The recommendations of Carter (1953), and Hickox (1954) form the basic criteria for the design of oil expression machinery up to today (Ward (1976); Garcia (1976); Norris (1964)).

2.2.6. CONCLUSION.

There have been no attempts to develop a fundamental mathematical model for the oil expression process. Previous work has produced empirical equations from data obtained from the end result of the expression process rather than from the process itself. The expression process is essentially a liquid - solid separation process. Before developing a fundamental theory on the expression process there is need to review the literature on liquid - solid separation process in materials other than oilseeds.

2.3. EXPRESSION MODELS FOR OTHER MATERIALS.

Solid-liquid separation by the action of mechanical forces has been studied in the expression of plant juice protein from forages, and consolidation of soils. Filtration is another solid - liquid separation process where mechanical forces are used but filtration theories and equipment are only applicable in the separation of relatively thin or pumpable slurries (Gurnham and Masson (1946)). Apart from consolidation of soils other expression studies have by and large produced empirical models.

2.3.2. EXPRESSION OF PLANT JUICE PROTEIN.

There have been several attempts to offer a theory on the expression of plant juice protein from agricultural products (alfalfa leaves and stems - Koegel *et al* 1972, 1973 a,b, 1974; Holdren *et al* 1972 and aquatic vegetation - Aboaba *et al* 1972, 1973).

2.3.2.1. Pressure - height - time model for the expression of juices from alfalfa leaves and stems.

Koegel *et al* (1972, 1973, a,b, 1974) have studied the expression of plant juice protein from alfalfa leaves and stems. They divide the process into two parts: maceration or rupturing of the plant cells and fractionation - the expression of the juice from the macerated leaves and stems. In the maceration process the cell wall is assumed non-porous and the rupture properties of the cell wall are considered with uniaxial force, hydrostatic force, uniaxial and shear forces, and extrusion orifices. They conclude that for maximum rupturing of the cell wall, extrusion through an orifice plate with holes of 3.2 mm diameter offers the best results (Koegel et al 1973). Acknowledging that the fractionation (expression) process is a case of flow through porous medium and the most fundamental relationship in this field being Darcy's law, Koegel et al 1972 decided to develop an empirical relationship to describe the process because of the "seemingly insoluble problems in developing a mathematical model to predict the amount of liquid expressed from macerated alfalfa". Their equation which is applicable at ambient temperature and an initial moisture content of M_i = 66% w.b. and final moisture content of 30% w.b. was:-

$$M_t / M_i = \exp(-(P^{0.2875}\, T^{0.2648}\, H^{0.07759})) \qquad (4)$$

where M_t = moisture content of forage after time t (s) (w.b)

M_i = initial moisture content (w.b.)

P = applied pressure (689.5 - 6895 kPa)

T = holding time in seconds (0 - 150s)

H = a thickness factor - kg solids per sq. metre of cylinder area.

As in equations (1) - (3) for oil expression equation (4) is developed from data obtained at the end of expression test. However, it is significant in equation (4) that the exponent of P and t are almost equal and larger than the exponent for H whereas in equations (1) and (2) the exponent for t was much smaller than the exponent for P. This is possibly because equations (1) and (2) were developed from data where t was greater than 1800s whereas in equation (4) t varied from 0 - 150s. In the latter case it is reasonable to assume a greater variation in the rate of expression with time.

2.3.2.2. Density - volume - weight model.

Holdren et al (1972) have developed an equation based on mass balance to describe the expression of juices from forages by mechanical forces. Their equation related the fraction of juice separated to the density of juice, density of forage when juice separation commences and final volume of solids i.e.

$$J = 100\ C_1\ \rho_1 \left(\frac{1}{\rho_1} - \frac{V_2}{W_1}\right) \qquad (5)$$

where J = % of original weight of forage separated as juice.

C = a constant representing fraction of expressed fluids that is juice.

ρ_l = density of expressed juice.

W_1 = initial weight of forage loaded into separation device.

ρ_1 = density of forage when juice separation begins = W_1/V_1

V_2 = final volume of solids left behind.

The development of equation (5) is based on data obtained at two instances of time during the expression process: (i) point when juice separation begins (ii) the end of the expression process. Equation (5) is independent of such important expression parameters as applied pressure and duration of pressing and as such is of limited practical and theoretical value.

2.3.3. SOIL CONSOLIDATION.

The consolidation of soils or the expression of water from between soil particles by application of a load is perhaps the only process which has been studied fundamentally although some attempts have been made to apply fundamental theories to the expression process in other products as will be described in Section 2.4

Two basic principles are used in studies of the consolidation process:-

(a) The effective and pore pressure principle: Terzaghi (1943) showed that when a pressure is applied to a saturated soil mass (no air voids) the applied pressure can be divided into 2 parts:

$$\sigma_t = \sigma_e + u \qquad (6)$$

where σ_t = total applied pressure.

σ_e = part of the applied pressure carried by the solid skeleton of the soil.

u = part of the applied pressure carried by the liquid phase of the soil.

(b) Darcy's law of flow through porous medium

$$\dot{q} = \frac{k}{\gamma_w}\frac{du}{dz} \qquad (7)$$

where $\dot{q}$ = rate of flow of liquid (water per unit time time and unit area (m/s)

k = Darcy's Coefficient of permeability (m/s)

du/dz = hydraulic gradient in the Liquid (pressure difference du over heigh dz) (N/m^3)

γ_w = Weight of unit volume of liquid (water) (N/m^3)

The consolidation process is well explained by the piston spring analogy proposed by Terzaghi (1943) shown in Fig. 4. The spring represents the solid matrix of the soil which is assumed to behave elastically and the water represents the water in the soil. When a load is applied on this piston and spring with the valve closed all the applied pressure is carried by the water ($\sigma_e = 0$, $u = \sigma_T$). If the valve is opened flow of water will commence and as this progresses the applied pressure will be progressively carried by the spring (Fig. 4). The flow of water will be governed by the resistance of the channels and the fraction of the applied pressure which is carried by the water. As the water flows and the fluid pressure is dissipated an equation governing this rate of dissipation is required to solve the consolidation process. By considering a small infinitesmal mass of soil and applying Darcy's law and conservation of mass, the consolidation process in soils is governed by the partial differential equation : (Taylor (1948) Wilun (1972) Lambe and Whitman (1969)).

$$C_v (\partial^2 u/\partial z^2) = (\partial u/\partial t) - (\partial \sigma_T/\partial t) \qquad . (8)$$

where u = pressure in liquid phase.

σ_T = total applied pressure

z = co-ordinate z in the direction of fluid flow (one dimensional fluid flow is considered).

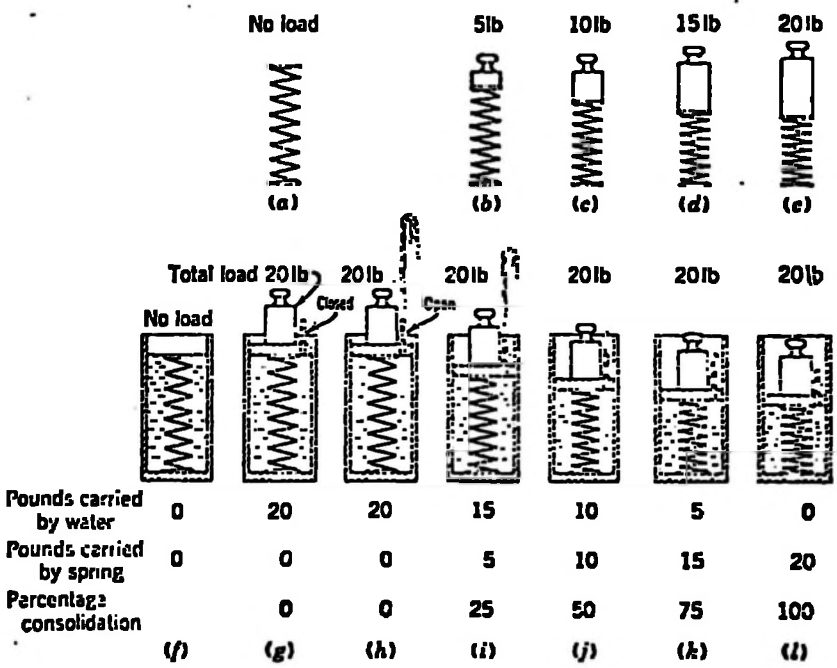


FIG. 4. The piston and spring analogy.

From Taylor (1966)

t = time.

C_v = a constant called coefficient of consolidation which describes the material properties of the soil.

The partial differential equation (8) has been solved for the case of constant applied load (i.e. $\partial\sigma_t/\partial t = 0$) and it reduces to the commonly encountered mathematical physics equation of diffusion:

$$C_v\,(\partial^2u/\partial z^2) = \partial u/\partial t \tag{9}$$

By use of the solution to the equation (9) for the boundary and initial condition of any soil mass and Darcy's law, the settlement (which for saturated soils is equal to the volume of water expressed from the soil) can be calculated. The above analysis applied to completely saturated soils (although it could be used to give approximate solutions to soils of about 95% and above saturation (Lambe and Whitman (1969)). The solution for partly saturated soils consolidation problem is by and large unsatisfactory. Several attempts have been made to modify equation (8) to extend it to solution of partly saturated soils consolidation problems. (Jennings and Burland (1962); Bishop and Blight (1963)- Matyas and Radhakrishnam (1968); Barden *et al* 1972). In consolidation of partly saturated soils the following points are considered (i) the chemical interaction between the air and water - solubility of air in water and most other liquids increases at elevated pressures,(ii) whether the air is in a continuous phase and hence the permeability of the air has to be considered or is occluded as bubbles in the water and hence a compressible liquid is being expressed. (Barden *et al*,1972).

2.3.4. EXPRESSION OF JUICES FROM AQUATIC VEGETATION.

In studies on compression characteristics and dewatering properties of aquatic vegetation (myriophyllum spicatum) Aboaba *et al*.1973 have compared the dewatering process to the consolidation process in soils. Using an equation developed for the computation of coefficient of permeability of soils they compute values of the permeability coefficient (K) of aquatic vegetation for different void ratios and applied pressures (0 - 1379 kPa). They then suggest that the value of K computed could be used with Darcy's law in the form

$$V_x = K(\partial P/\partial x) \qquad (10)$$

where V_x = flow of juice in direction x (m^3/sm^2)

$\partial P/\partial x$ = pressure gradient in direction of flow (N/m^3)

K = coefficient of permeability (m^4/Ns)

They suggest that if K and $\partial P/\partial x$ are known it is possible to predict the flow of the liquid at any particular pressure. However, no results are presented. Further it would appear that the pressure P used in equation (10) is the total applied pressure i.e. they assume that all the applied pressure will be carried by the liquid phase. However, the aquatic vegetation (0.8sp. gravity) contains over 50% air by volume and it is unlikely that air is completely eliminated during chopping before expression as they suggest.

2.5 GENERAL EXPRESSION MODELS.

2.4.1. MODIFIED FORM OF DARCY'S LAW

Swartzberg et al 1977 have attempted to develop a more general equation for the mechanical expression of fluids from agricultural products. Their model was based on Terzaghi's approach of dividing the applied pressure into two components as summarized in equation (6). The rate of expression was based on a modified form of Darcy's Law (Equation (7)).

$$du/dz = \alpha \nu U/g \qquad (11)$$

where

du/dz = the fluid pressure gradient with respect to w - the dry non-expressible solids weight per unit area upstream from outflow surface. In contrast Darcy's law considers the total mass of material.

U = the superficial velocity of the fluid relative to the solid particles.

ν = the viscosity of the fluid

g = the gravitational constant

α = the specific flow resistance in the press cake per unit weight of the non-expressible solids.

The expression $\alpha\nu/g$ is equivalent to the inverse of the permeability coefficient in Darcy's Law.

Equation (11) was applied to the expression of fluids from alfalfa leaves, applecubes, and coffee grinds. The magnitude of the fluid pressure, u, was not measured but was estimated from their Instron UTM compaction readings:-

$$u = C\ (\sigma_T - \sigma_m) \qquad (12)$$

where σ_T = the total applied pressure.

σ_m = the total applied pressure at which expression of liquids from the press cake commenced.

C = a constant varying from 2 - 3 depending on the material.

This infers that the fluid pressure is constant throughout the expression process if σ_T is constant.

This cannot be true because the flow through the porous medium dissipates the pressure in the fluid. Secondly since the constant of proportionality C varied from 2 to 3, this means that before liquid expression commences from the material (i.e. $\sigma_m = 0$) the fluid pressure u will be 2 to 3 times the applied pressure σ_T whereas in reality u must be equal to or less than σ_m. They explain this discrepancy as being due to experimental errors. They anticipate refining the model in future when they have obtained more reliable data of the variation of ,α, the specific resistance to flow and σ_T, σ_m and u.

2.4.2. CONTINUUM MECHANICS APPROACH

Gustafson et al 1977 a, b have analysed the compression of a gas-solid - liquid media using continuum mechanics principles. The main objective of their research was to mathematically model the problems of cracking and splitting of skins of biological materials such as fruits and vegetables prior to harvest and mechanical damage during harvest and storage. Such problems arise due to variation of internal conditions such as turgor pressure and variation in external loading.

The total stress of the bulk material is expressed as:

$$\tau_{ij} = \delta_{ij} + \delta_{ij}\ (\sigma_f + \sigma_g) \qquad (13)$$

Where σ_{ij} result from forces applied to the solid part of the body, σ_{ij} is the Kronecker delta and σ_f and σ_g result from forces applied to the liquid phase and gas phase respectively. The fluid forces σ_f and σ_g are a product of liquid and gas pressures P_f and P_g and the liquid and gas porosities f and g respectively.

$$\sigma_f = - fP_g \qquad (14)$$

$$\sigma_f = - gP_g \qquad (15)$$

where f = Liquid Porosity = $\dfrac{\text{Volume of Liquid}}{\text{Volume of Bulk Material}} = \dfrac{V_f}{V_g}$

g = Gas Porosity = $\dfrac{\text{Volume of gas phase}}{\text{Volume of Bulk Material}} = \dfrac{V_f}{V_b}$.

The system is considered in equilibrium and P_f and P_g are assumed constant throughout and gas-solid-liquid system. Using strain energy principles they developed equations for calculating the stress distribution in a spherical fruit for two cases:

(i) Changes in the internal fluid pressure (Turgor pressure).

(ii) Flat plate compression of the fruit.

In both cases they consider a jacketed condition in which the skin of the fruit is intact and an unjacketed condition in which the skin is split and the fluids are allowed to escape. For the unjacketed condition the fluid and gas pressures are assumed to be zero in the formulation of their equations. For the jacketed case P_f and P_g take finite values which are a function of the applied pressure in case (ii). Using finite element methods the equations are used to calculate the stresses in a spherical body of 6.67 cm diameter enclosed by a thin layer of material of higher elastic modulus (to simulate a material such as a tomato). They claim "the gas-solid-liquid model developed, used in conjunction with the finite element mothod, has been shown to be capable of describing the stress distribution within a tomato created by variation of internal conditions such as turgor pressure. Good agreement exists, in principle between results of numerical examples and experimental observations such as those by Considine and Kriedmann (1972)". It is claimed further that it is not necessary in this method to describe the structure of individual cells or the type of interaction which occurs between cells.

Measurement of material properties is made on bulk materials and not generalised from individual cells.

The lack of validity of some of their basic assumptions to the expression process renders Gusta-fson's _et al_ model inapplicable to the expression process. For example in the unjacketed cases they assume $P_f = P_g = 0$ which is unlikely as fluids will flow only when there is a pressure gradient. Secondly although acknowledging that the stress - strain relations include phenomena which may depend on the physical chemistry of the gas - solid - liquid system they do not consider the solubility of the gases in the liquid phases when pressures are elevated. Finally it is unlikely that we can ignore the action of individual cells and interaction between them in the expression process as has been suggested by Gustafson. _et al_ (1977).

2.5 INADEQUACIES OF EXISTING MODELS.

Apart from consolidation of soils, it is clear from the above literature review that there has been little attempt to develop fundamental theories of the expression process. Empirical equations have been developed by Koo (1942); Baskerville *et al* (1947); Koegel *et al* (1972, 1973), which in reality describe the situation at the end of the test rather than the expression process itself. The existing theories in the oil expression industry are emphatic on the need to rupture the cell walls of the oilseeds prior to oil expression even though little microscopic disruption of cells in rolled cottonseed flakes had been observed by Woolrich and Carpenter, (1935). The effect of important process variables such as temperature are not well understood. Attempts by Aboaba *et al* (1972), and Swartzberg *et al* (1977) to model the expression process using basic principles developed in soil mechanics have not yielded a successful model for the process. A need exists therefore to study the expression process using basic engineering principles. The elucidation of the fundamental expression mechanism allied with a knowledge of the physical and thermal parameters affecting the process should enable the design of more effective oil expressio n equipment.

2.6 SPECIFIC OBJECTIVES OF THE PROJECT:

The preceding literature review has led to the formulation of the following project objectives:

(1) To experimentally study the mechanism of oil expression from cashew and rapeseed using mechanical compression on the Instron Universal Testing Machine (UTM). The test conditions will include the variation of:

(a) Rate of straining in drained compression.
(b) Rate of loading in drained and undrained compression.
(c) Temperature of oil expression.
(d) Pre-treatment of the oilseeds before oil expression.

These tests will provide data on:

(a) Rate of oil expression during tests.
(b) Division of the applied pressure between the solid matrix of the oilseeds and oil phase during both drained and undrained compression.
(c) Compression characteristics of the oilseeds.

(2) To elucidate the microstructure of cashew and rapeseed before and after oil expression in (1) above, and to determine the changes on cellular structure caused by oil expression.

(3) To build a mathematical model of the process of expression of oil from vegetable oilseeds using fundamental principles such as Darcy's law of flow through porous media using data obtained in (1) and (2) above.

CHAPTER 3: EXPERIMENTAL STUDIES.

3.1. INTRODUCTION.

The expression process normally involves applying compressive forces to the oilseeds enclosed in a suitable filtering or retaining envelope. To simulate these compressive forces acting on the oilseeds in a typical oil expression machine, oil expression was studied in plunger/cylinder test rigs on the Instron Universal Testing Machine (Instron UTM). Two types of Instron UTM were used for these studies.

(a) Constant Rate of Strain Instron UTM: (CRS - Instron UTM) Floor model TT -CM in which a moving crosshead to which the plunger is attached imposes a force on the oilseeds in a cylinder placed between the anvil and the stationary lower platen. The crosshead moves at a constant speed which can be varied from 0.1 to 500 mm/min.

(b) Constant Rate of Loading Instron UTM: (CRL - Instron UTM) - Floor model 1274 in which an actuator to which the cylinder is attached moves upwards and is brought into contact with the plunger which in this case is attached to a stationary crosshead. The movement of the actuator can be both linear and non-linear and hence the capability of this Instron UTM to generate a linearly increasing load and non-linear strain.

The preliminary tests were done on the Constant Rate of Strain Instron UTM (Section 3.2) while the final expression tests (Section 3.3.) were done on the Constant Rate of Loading Instron UTM. (CRL Instron UTM).

3.2. OIL EXPRESSION AT CONSTANT RATE OF STRAIN.

3.2.1. APPARATUS.

A plunger-cylinder rig was constructed as shown in Fig. 5 while Fig. 6 shows the rig attached to the Instron UTM. The plunger was attached to an extension anvil which in turn was attached to the crosshead of the Instron UTM. The cylinder was placed on top of the load cell. The base of the cylinder contains a shallow oil catch basin (25 mm diameter and 4 mm height) and a drainage channel (3.0 mm dia) which transfers the expressed oil to the outside. The basin is covered by a mild steel porous disc (40 mm in diameter with holes of 2 mm dia - giving a drainage area of 4.6%). On top of this porous disc a pair of 250 mm stainless steel wire mesh together with standard laboratory filter paper (Whatman no 4) were placed to stop any solid extrusion with the oil. The friction between the plunger and cylinder was negligible and the oil acted as a lubricant. For instance loading of the plunger without oilseeds in the cylinder produced less than 0.5% deflection on the load printout when the sensitivity was set at the value used in expression tests (50 kN). Other details about the plunger/cylinder rig - e.g. dimensions and materials used are shown in Fig. 5.+ 6.

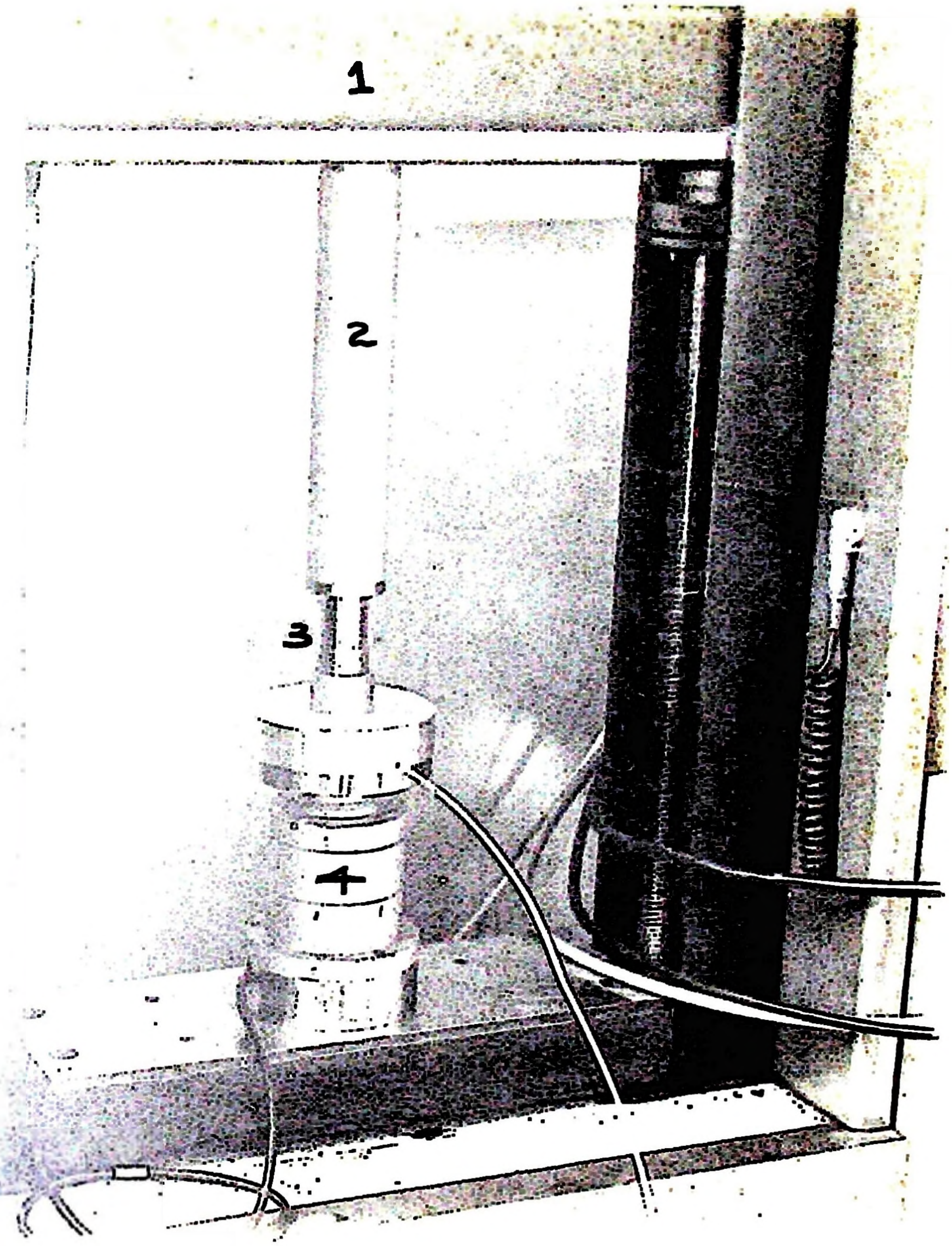


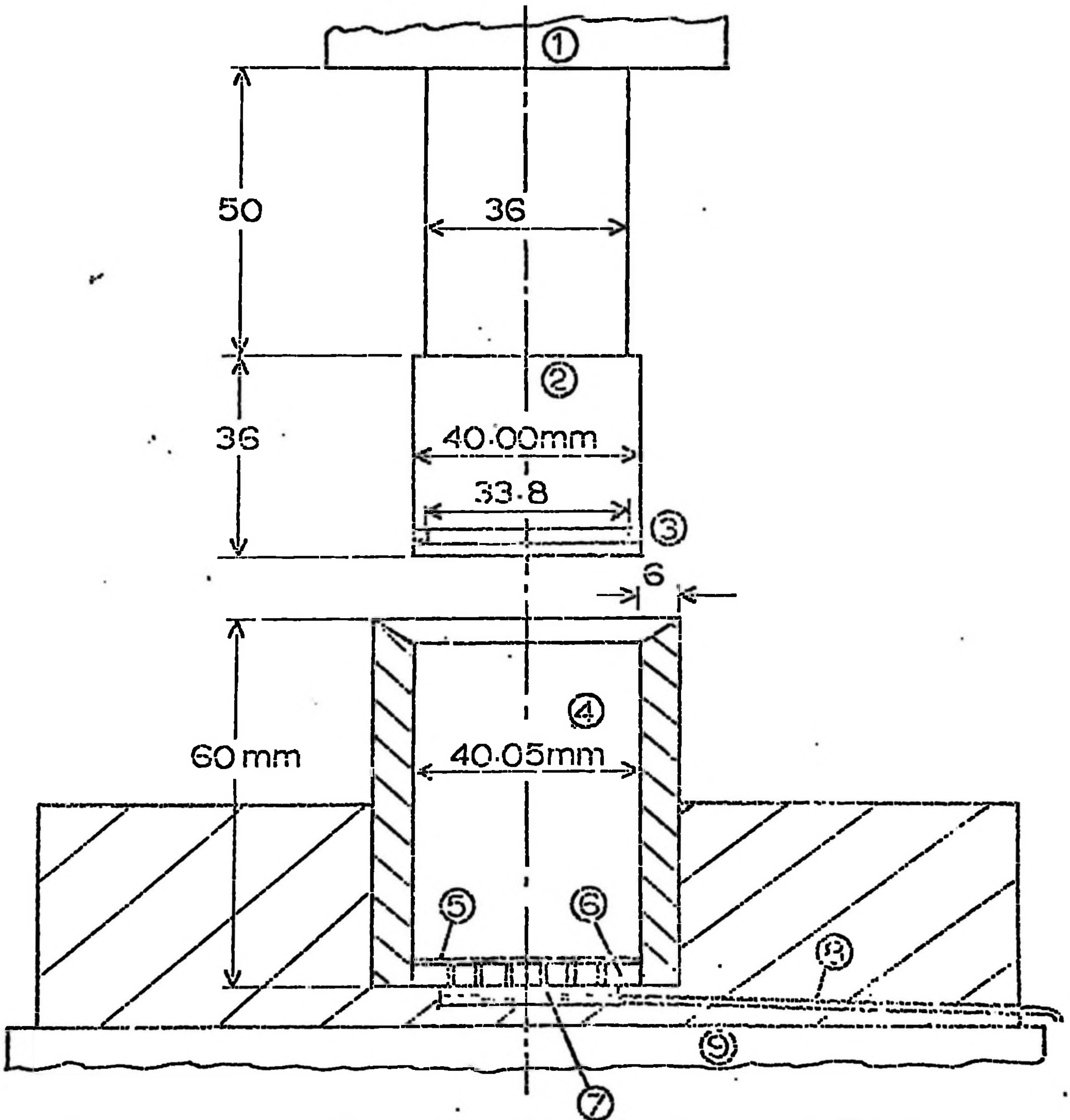
FIG. 5. EXPRESSION RIG ON THE CONSTANT RATE OF STRAIN INSTRON UNIVERSAL TESTING MACHINE.

1. - Crosshead 2. Extension Anvil

3. - Plunger/cylinder rig 4. Loadcell.

FIG 6: A SCHEMATIC DIAGRAM OF THE CONSTANT RATE OF STRAIN OIL EXPRESSION RIG.

(All dimensions in millimetres).



1) Extension Anvil of Instron UTM.
2) Plunger (mild steel)
3) Rubber 'O' rings (3.531 mm dia)
4) Cylinder (mild steel)
5) Wire mesh (a pair 0.3mm thick 250μm mesh) + Whatman No.4 filter paper
6) Porous disc (mild steel, 5 mm thick, 4.6% drainage area).
7) Oil catch basin (3mmX30mm dia)
8) Oil Exit channel (3 mm dia).
9) Load cell of instron.

3.2.2. EXPERIMENTAL PROCEDURE.

Forty kilogrammes of rapeseed was obtained from a grain merchant in Dublin (Irish Seed Co. Ltd., Dublin 1) (1975 Harvest - variety Jinx) and 30 kilogrammes of cashew kernels were obtained from a grain merchant in London (G.C.Williams Ltd., Marklane, London) Variety Indian - whole (1975)). Both the batches were analysed for their moisture, and oil content in accordance with official methods of the Association of Oil and Agricultural Chemists (AOAC 1975)

In all tests 30g of the oilseeds were placed in the cylinder which was enough to fill the cylinder to the top. The plunger was then manually brought to top of the cylinder which was taken as the zero position and pressing commenced. A crosshead speed of 2 mm/min was used in all tests, unless otherwise stated which was the highest speed possible at loads greater than 40 kN without automatic load interruption. The amount of oil expressed was obtained by weighing the cake after oil expression and taking the difference from the initial weight of the seeds. No attempt was made in these preliminary tests to monitor the rate of oil expression or the fluid pressure.

In the elevated temperature tests the environmental chamber of the Instron UTM was used to control temperature in the range of 20 - 140^{o}C. Thirty grams of the oilseeds were placed in a thin layer in a metal dish in the environmental chamber and temperature set at 20°C. One layer of cashew kernels and 4 layers of rapeseed were used. Heating was commenced and when the temperature of the test had been reached heating was continued for the duration of test (30 minutes, 1 hour to 2½ hours). After the time set for heating had been reached the chamber door was opened and the seeds transferred to the expression rig. This operation took less than 30s and in most cases the drop in temperature was less than 3°C. The expression of oil was commenced immediately with a crosshead speed of 2 mm/min until the maximum load used (45kN) had been reached. At this stage the crosshead was stopped and the cake removed from the rig and weighed. In another series of tests the same procedure was used with the crosshead speed (straining rate) being varied from 0.1 mm/min to 2 mm/min at temperatures of 20°C, 80°C, and 120°C. To determine the effects of pre-treatment before heating, cashew kernels were split to 2 cotyledons, half a cotyledon each piece, and ground to pieces of between 3.2-6.4 mm^3 in size and oil expressed from them at 120°C.

Although the seeds were of low moisture content (4% mc.wb) at each temperature of test 30g of oilseeds were placed in a metal dish and placed in the environmental chamber and given the same heat treatment as those to be expressed. Their loss in weight was taken as the moisture correction factor for the weight of expressed oil. At 140°C for example, the moisture correction factor was 1.12g for cashew and 1.32g for rapeseed. The amount of oil expressed was determined by taking the difference:

Weight of oil expressed = 30.0g - (Moisture Correction factor + weight of cake after oil expression)

and the % of oil expressed

$$= \frac{\text{Weight of oil expressed}}{\text{Weight of oil originally present in 30g of oilseeds.}}$$

One 4 gm sample of the cake from each test was analysed in the laboratory after expression by the soxhlet method (AOAC 1975) to check if the amount of oil remaining in the cake corresponded with the experimental figures for the % of oil expressed. Before and after each test samples were examined under a microscope to determine any changes in the cellular structure of the oilseeds.

3.2.3. RESULTS.

3.2.3.1. Chemical analysis of rapeseed and cashew.

Ten samples each of cashew and rapeseed were analysed to determine their oil, moisture and protein content using recommended tests (AOAC 1975). The following average percentages were obtained: (± Standard Error)

	Oil	Moisture	Protein	Others
Rapeseed	43.7 ± 0.082	4.29 ± 0.04	21.1 ± 0.5	30.9
Cashew	41.7 ± 0.94	3.92 ± 0.03	17.7 ± 0.7	36.6

3.2.3.2 Compaction behaviour of cashew and rapeseed.

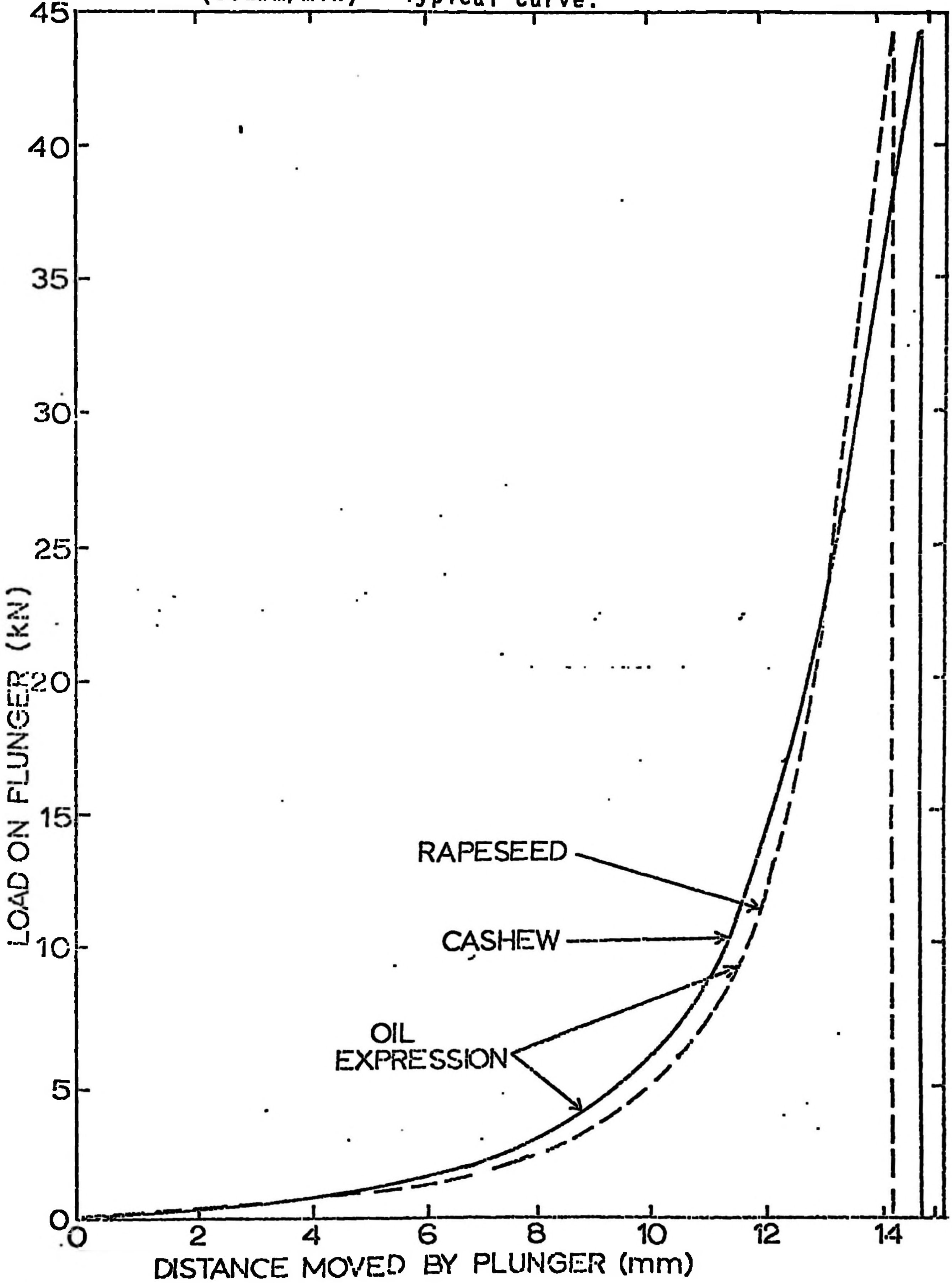
Initial tests were carried out on whole, untreated cashew and rapeseed at ambient temperature to determine their compaction behaviour under constant rate of strain. Figure 7 shows typical force - distance curves from these tests. The maximum load used in this case was 45 kN and oil begun to be expressed at low loads (About 4 kN for cashew and 10 kN for rapeseed). The conventional theory of oil expression (Norris 1964; Ward, 1976) emphasises the necessity of pretreatment processes - decorticating, pre-crushing and cooking - to rupture cell walls and immobilise the proteins before oil expression can commence. Because of this unexpected oil expression at low loads from untreated seeds at ambient temperature, tests were carried out to determine the effect of various loads and holding the load on oil expression.

3.2.3.3. Effect of maximum load and holding the load.

The effect of applied load on oil expression at ambient temperature from whole non-pretreated seeds is shown in Fig. 8. The load was raised at a constant crosshead

FIG. 7: COMPACTION BEHAVIOUR OF RAPESEED AND CASHEW UNDER CONSTANT RATE OF STRAINING.

(0.2mm/min) - Typical Curve.



speed of 2 mm/min to the desired level and immediately cut off representing a maximum duration of pressing of about 7 minutes. Surprisingly up to 50% oil was expressed under these conditions suggesting that neither mechanical pretreatment nor thermal pretreatment is required before substantial oil expression can occur. Microscopic examination of the oilseeds revealed little difference in cell structure before and after oil expression (cf Chapter 4). The seeds themselves showed little deformation virtually retaining their shape as shown in Figure 9a and b. The density, refractive index and moisture content of the expressed oil was determined in accordance with AOAC methods (Table 1). The density and refractive index figures obtained were within the range given by BS 631: 1967 for crude rapeseed oil (i.e. Ref. Ind for rapeseed oil (crude) 1.4720 at 20^{o}C according to BS631:1967).

Figure 8 shows that the oil expressed increases as the load is increased up to 20 MPa. Thereafter the effect of increasing the load further was minimal. This corresponds with the recommendations of Carter (1953) and Hickox (1954) that there was no advantage of using pressures of more than 13.8 MPa unless the final cake thickness was more than 25 mm thick for cottonseed. The final cake thickness was 22.5 mm for cashew and 22.4 mm for rapeseed for the highest load used (35.2 MPa). Secondly the amount of oil expressed from cashew was greater than that expressed from rapeseed at

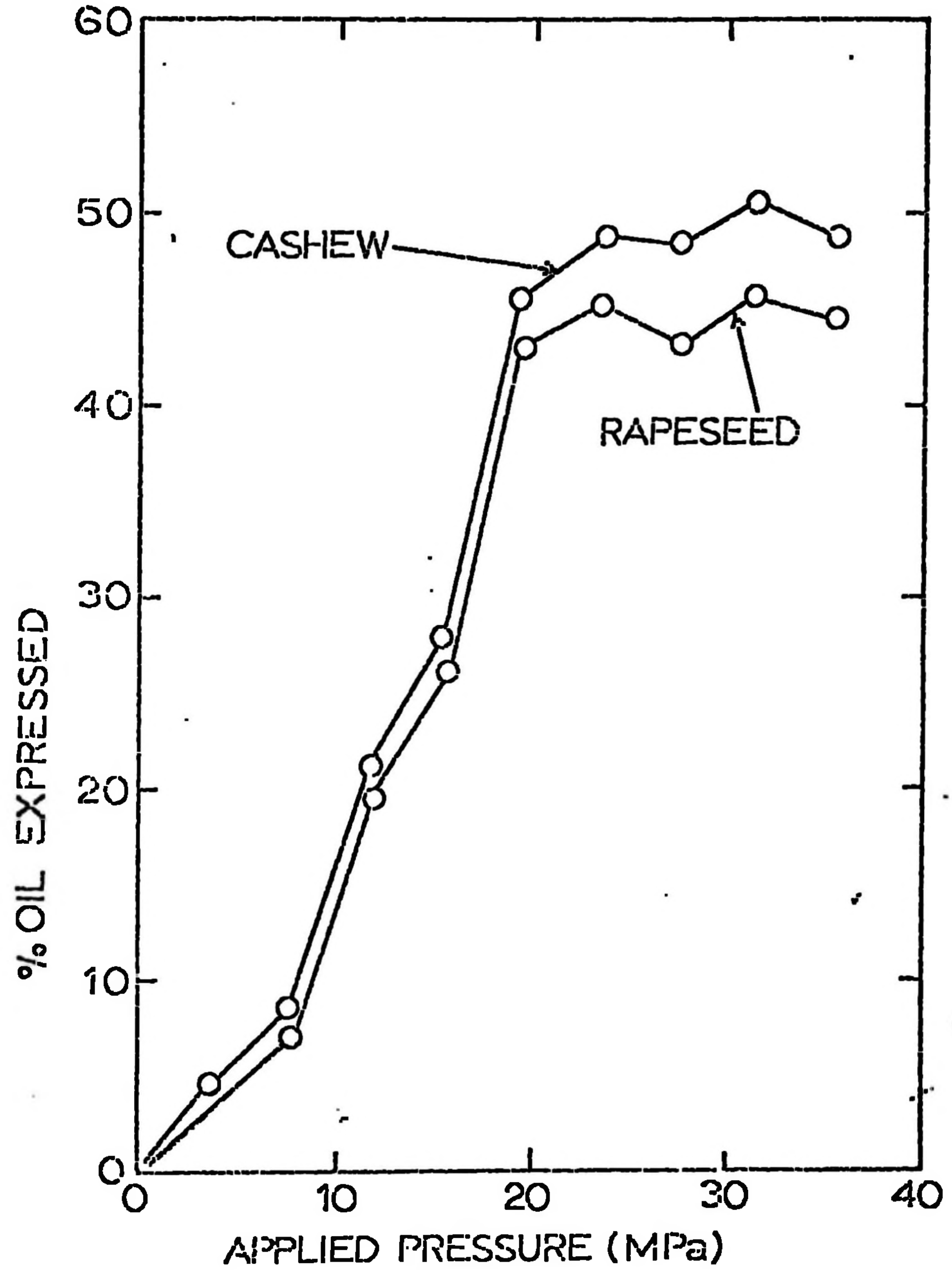


FIG. 8: EFFECT OF APPLIED PRESSURE ON OIL EXPRESSION. Load raised from zero at a constant straining rate of 2mm/min. Until desired pressure and immediately cut off. Oil expressed determined by weighing cake after expression.

TABLE 1: ANALYSIS OF EXPRESSED OIL.

The expressed crude oil was analysed according to AOAC methods. The following results were obtained at ambient temperature 15.5°C. Refractive Index corrected to 25°C.

Oil	Density Kg/m (15.5°C)	Refractive Index at (25°C)	Moisture % w.b.
Rapeseed	912	1.472	0.30
CASHEW	914	1.471	0.28

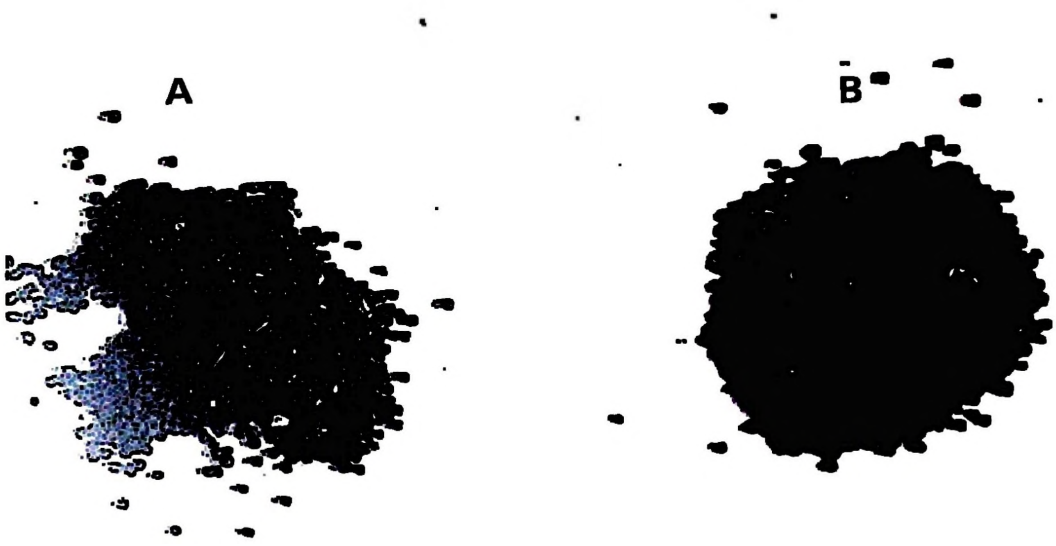


FIG. 9(a,b) RAPESEED AND CASHEW KERNELS BEFORE AND AFTER OIL EXPRESSION.

a) Rapeseed (above) A- Before B - After

b) Cashew (below) A - Before B - After

the same load. This could possibly be due to the internal structure of cashew, and the fact that cashew kernels were dehulled while rapeseed were not dehulled although the latter point should be counter balanced by the fact that the cashew kernels were larger than rapeseed.

By increasing the duration of holding the load up to 30 minutes at the maximum load (35.2 MPa) the oil expressed was increased to 60 - 70% as seen in Table 2.

Rewriting equation (1) (Koo (1942) cf section 2.2)

$$\ln(W_e/W_0) = \ln C + 0.5\ln P - 0.5z\ln\nu - 0.167\ \ln(t/60 \times 60)$$

where t = is in seconds.

$$\ln(W_e/W_0) = \ln C + 0.5\ln P - 0.5z\ln\nu - 0.167\ln 3500 + 0.167\ln t.$$

For constant temperature (hence ν constant) and pressure this reduces to:

$$\ln(W_e/W_0) = M_1 + M_2\ \ln t. \qquad (16)$$

where M_1 and M_2 are constants.

A plot of $\ln(W_e/W_0)$ against time (t) yielded a linear relationship for rapeseed and cashew respectively as follows for data in excess of 100s (Fig.10a,b and Table 2)

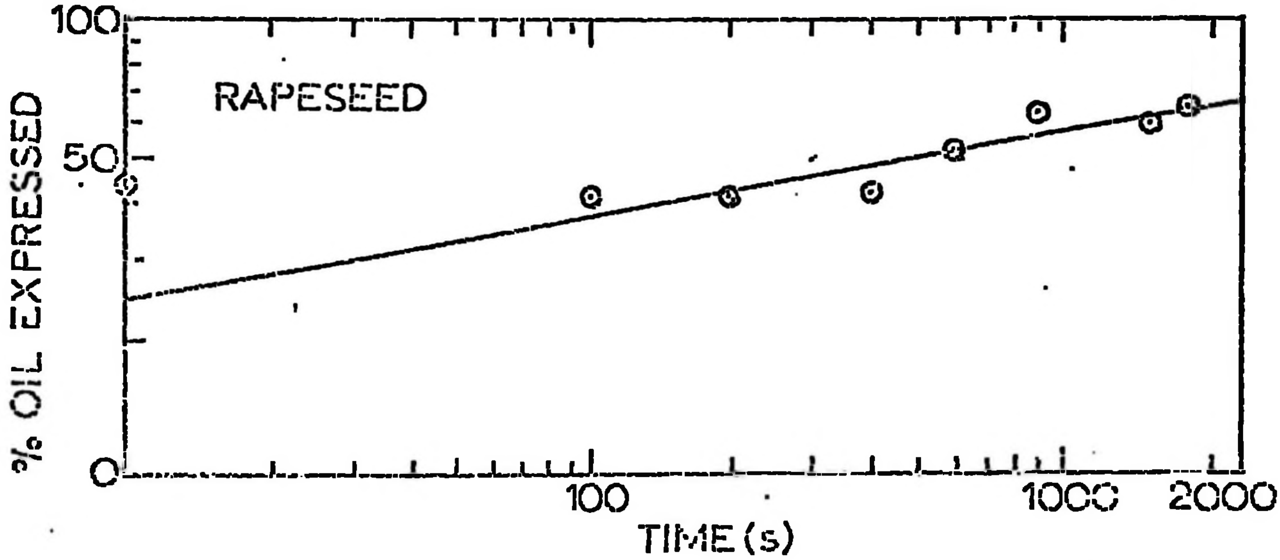
TABLE 2: EFFECT OF HOLD TIME ON OIL EXPRESSION.

A constant load of 45.0 kN (equivalent to a pressure of 35.2 MPa) for different times.

Time	% of total oil expressed	
s	Cashew	Rapeseed
0	48.9	44.5
100	48.5	41.3
200	49.5	42.1
400	51.2	41.9
600	57.5	51.2
900	67.5	62.1
1500	70.0	58.1
1800	69.2	62.8

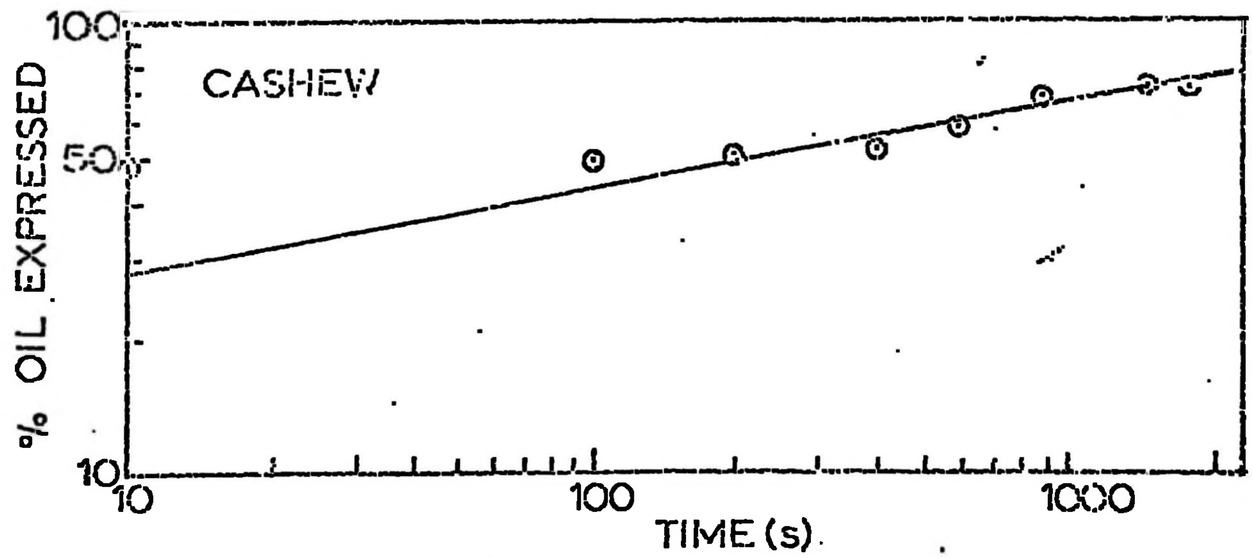
FIG. 10: APPLICATION OF EQUATION (1) TO DATA FOR RAPESEED AND CASHEW FOR DATA IN TABLE 2.

Equation: $\ln(W/W_0) \times 100) = M_1 + M_2 \ln(t)$



For Cashew Equation $M_1 = 2.86$ $M_2 = 0.16$

For Rapeseed Equation $M_1 = 2.94$, $M_2 = 0.14$.



for cashew:

$$\ln\left((W_b / W_0) \times 100\right) = 2.86 + 0.16 \ln t \qquad (17)$$

and for rapeseed:

$$\ln\left((W_e / W_a) \times 100\right) = 2.94 + 0.12 \ln t$$

An analysis of equation (2) (cf section 2.2) revealed that it could be rewritten as follows:

$$\ln (1 - W_b / W_0) = M_3 - M_4 \ln t$$

This yielded a non-linear relationship when plotted for data.

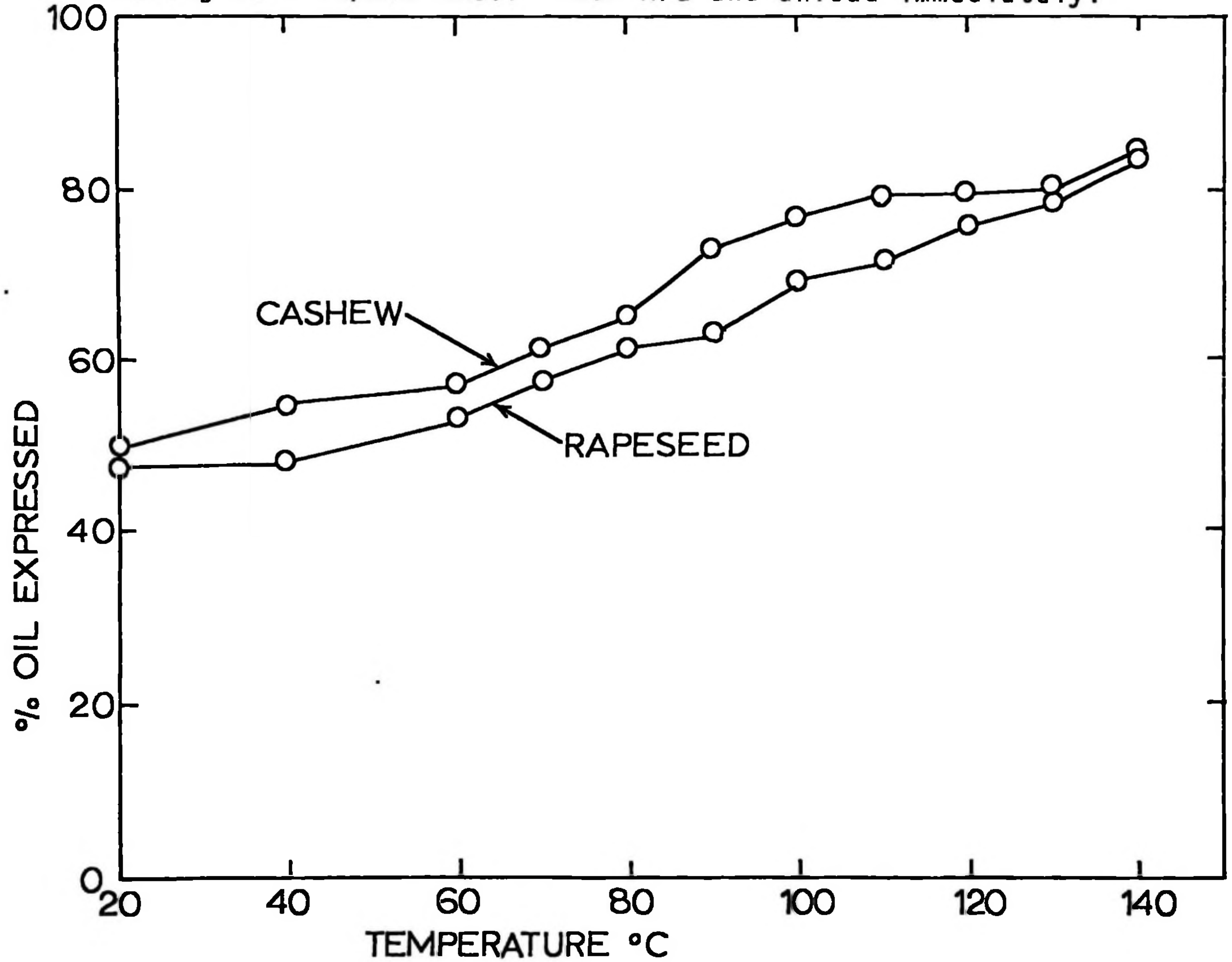
3.2.3.4. Effect of temperature on oil expression.

The effect of pre-heating whole cashew and rapeseed kernels before oil expression is shown in Fig. 11. The temperature was raised from 20°C to the desired temperature which was maintained for 1 hour. The oilseeds were then transferred to the expression rig and expression commenced immediately at a crosshead speed of 2 mm/min until a load of 45 kN (35.2 MPa pressure) was attained. The crosshead was then stopped and the load dropped to zero immediately. The amount of oil expressed was obtained by weighing the cake after expression and subtracting this from original weight of the seeds (30g). The moisture correction

FIG. 11. EFFECT OF TEMPERATURE ON OIL EXPRESSED.

Heating from 20°C to temperature and maintained for 1 hour

Pressing at 2 mm/min until 35.2 MPa and unload immediately.



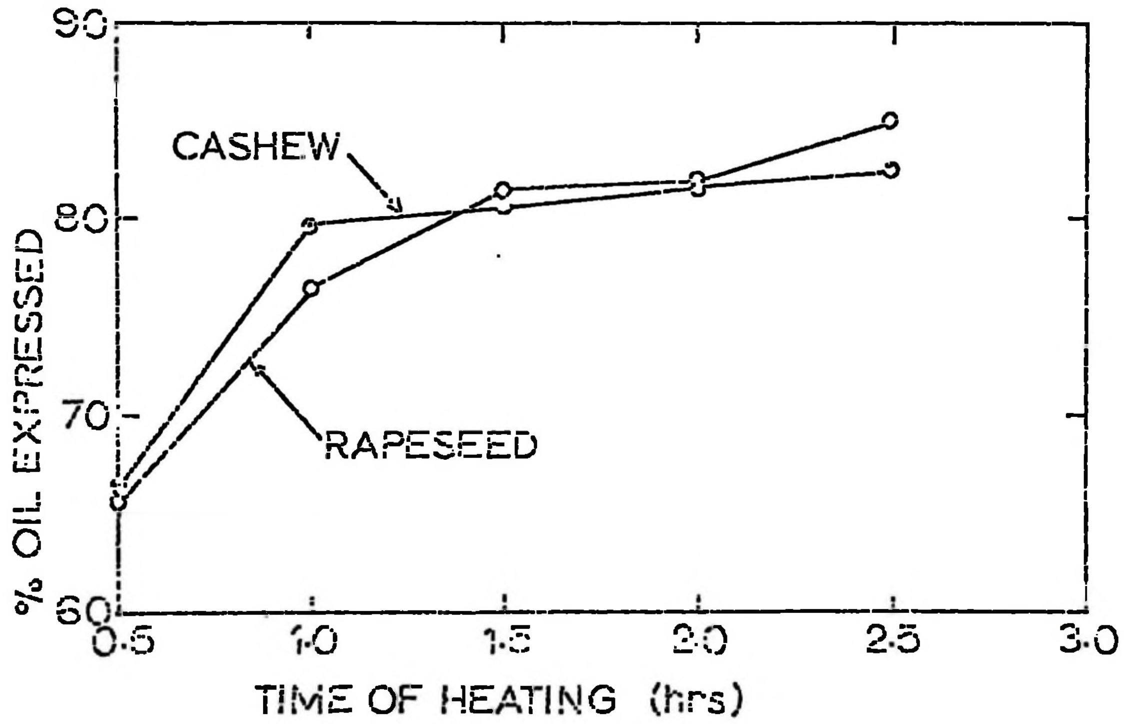
factor was obtained as explained in Section 3.2.2 The data in Fig. 11 represent the average of three tests. The amount of oil remaining in the cake was checked by the soxhlet method (AOAC,1975) and good agreement (<0.5% difference) was obtained. Detailed data from which Fig. 11 was obtained are shown in Appendis 1. The data in Fig. 11 reveal that the amount of oil expressed increases as the temperature is increased. Secondly, the amount of oil expressed from cashew is higher than in rapeseed at all temperatures. Due to the small size of the rapeseed kernel compared to cashew it had been expected that the action of heat would have resulted in more oil being expressed from rapeseed than from cashew. This is possibly due to the hull on the rapeseed and differances in internal structure of the two seeds as will be discussed in later sections.

3.2.3.5. Effect of heating time, on oil expression.

The effect of increasing the duration of heating at 120^{o}C from 1 hour to 2½ hours on oil expression is shown in Fig. 12. Heating cashew for 2.5 hours produced 3% more oil than heating for 1 hour For rapeseed however,. the effect was more pronounced increasing the amount of oil expressed by about 9%.

FIG. 12: EFFECT OF HEATING TIME ON OIL EXPRESSION.

Heating from 20°C to 120°C and temperature maintained at 120°C for the required duration. Pressing 2 mm/min until 35.2 MPa and unload immediately.



3.2.3.6 Effect of pretreatment.

The effect of reducing the seed size for cashew kernels before heating and expressing is shown in Table 3 where the seeds were heated from 20°C to 120°C and temperature was maintained for 1 hour at 120°C. Pressing was as described in section 3.2.3.4. There was little difference in the amount of oil expressed in the first three pretreatments. However, the amount of oil expressed from ground seeds was much higher than in any other case (Table 3).

3.2.3.7 Effect of varying the straining rate.

Whole seeds without any pre-treatment were heated for one hour at 20°C, 80°C and 120°C and then the oil was expressed at crosshead speeds 0.1, 0.2, 0.5, 1,2, mm/min until a load of 35.2 MPa. The results of varying the crosshead speed (straining rate) and temperature are shown in Fig. 13. The amount of oil expressed increased as temperature increased and as straining decreased.

TABLE 3: EFFECT OF REDUCING SEEDSIZE OF CASHEW AND TEMPERATURE ON OIL EXPRESSION.

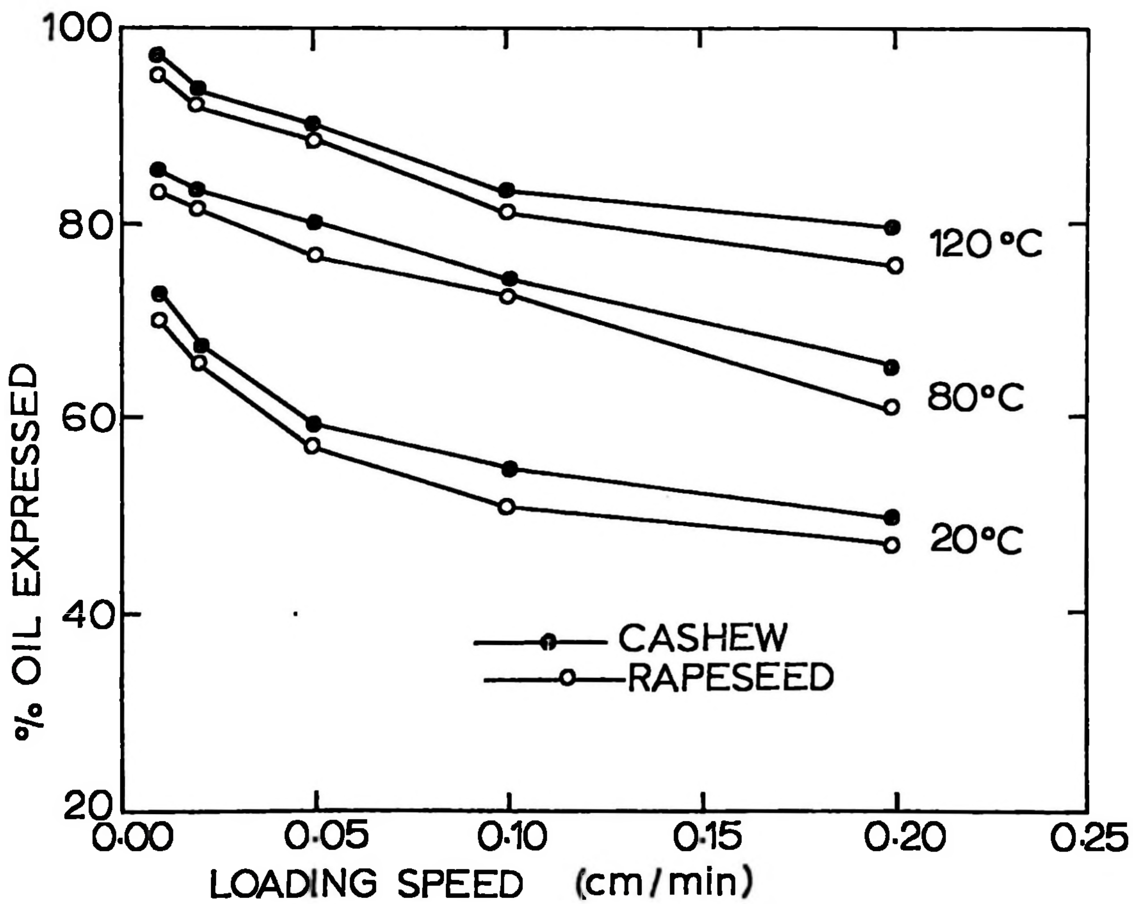
All samples (30g) preheated to 120^{o}C and held for 1 hour. Samples then loaded at 2 mm/min until 35.2 MPa and the load was then immediately removed.

Treatment	Average oil expressed (g)	Moisture Correction factor (g)	Oil expressed (g)	% Oil expressed
Whole cashew kernels	10.83	0.90	9.93	78.9%
Each Cotyledon separate	10.92	0.90	10.92	80.48%
Each cotyledon cut to 2 halves	11.06	0.94	10.12	81.29%
Ground to pieces of size ≈ 3.4 - 6.4 mm^3	13.05	1.12	11.93	95.82%

FIG. 13: EFFECT OF VARYING LOADING SPEED AND TEMPERATURE ON OIL EXPRESSION.

Heating: From 20°C to desired temperature and held for 1 hour.

Pressing: At loading speed until 35.2 MPa.



3.3. OIL EXPRESSION AT CONSTANT RATE OF LOADING FOLLOWED BY CONSTANT LOAD EXPRESSION.

3.3.1. APPARATUS.

The experiments in this section were done useing the Instron 1274 Universal Testing Machine because it permitted the application of a constant rate of loading test regime Instron 1274 UTM).

The basic features of the Instron 1274 UTM are_(cf Fig.14).

(a) A fixed crosshead to which a load cell (0 - 500 kN) is attached.

(b) An actuator with maximum amplitude of 50 mm from it's mean position whose movement can be both linear (constant rate of strain) or non-linear (hence the ability of the Instron 1274 to generate a linearly increasing load).

(c) A control panel with a digital readout and strip-chart recorder. The linear function (either strain when load is non-linear) is normally recorded on the stripchart recorder whereas the non-linear function is read from the digital readout.

To this Instron 1274 UTM a new expression rig was attached as shown in Fig. 14. The diameter of the cylinder in this case was 75 mm. Fig. 15 is a section through the expression rig. The base of the cylinder contains a shallow oil catch basin and a drainage channel (6 mm diameter) which transfers the oil expressed to a graduated cylinder which measure the

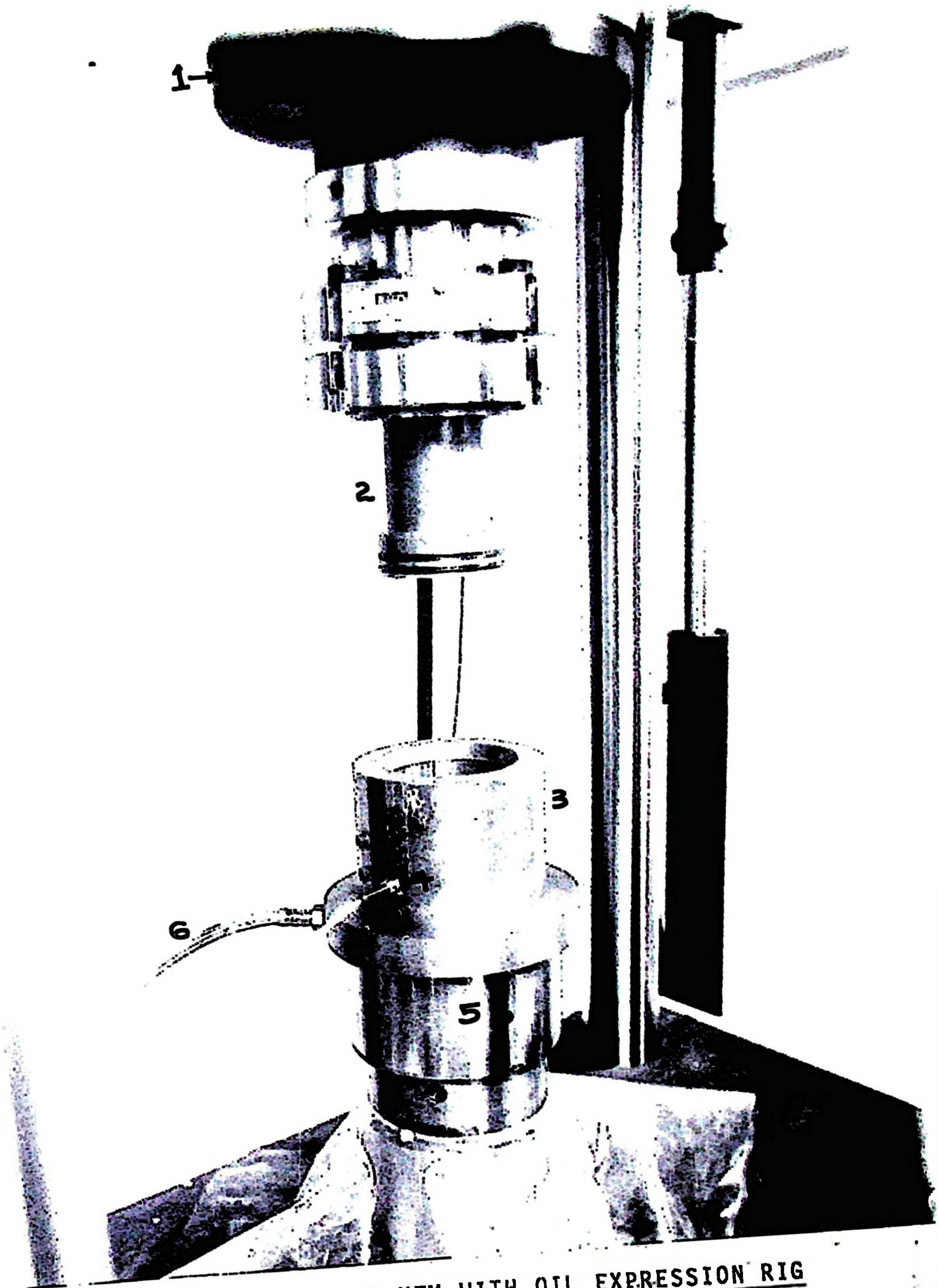


FIG. 14: INSTRON 1274 UTM WITH OIL EXPRESSION RIG ATTACHED.

1. - Loadcell fixed to stationary crosshead.
2. - Plunger.
3. - Cylinder.
4. - Pore pressure transducer.
5. - Actuator.
6. Oil drainage tube.

FIG. 15: OIL EXPRESSION RIG FOR INSTRON 1274.

A - Porous disc(Fig.16);
C - Wire mesh + Filterpan (1000 m X 250 m)
G - Base connected to actuator of Instron.
H - Plunger connected to load cell of Instron.
B - Pore pressure holes,
F - Cylinder.
E - 'O' rings 3.1mm dia.
D - Drainage channell.
Dimensions - mm.

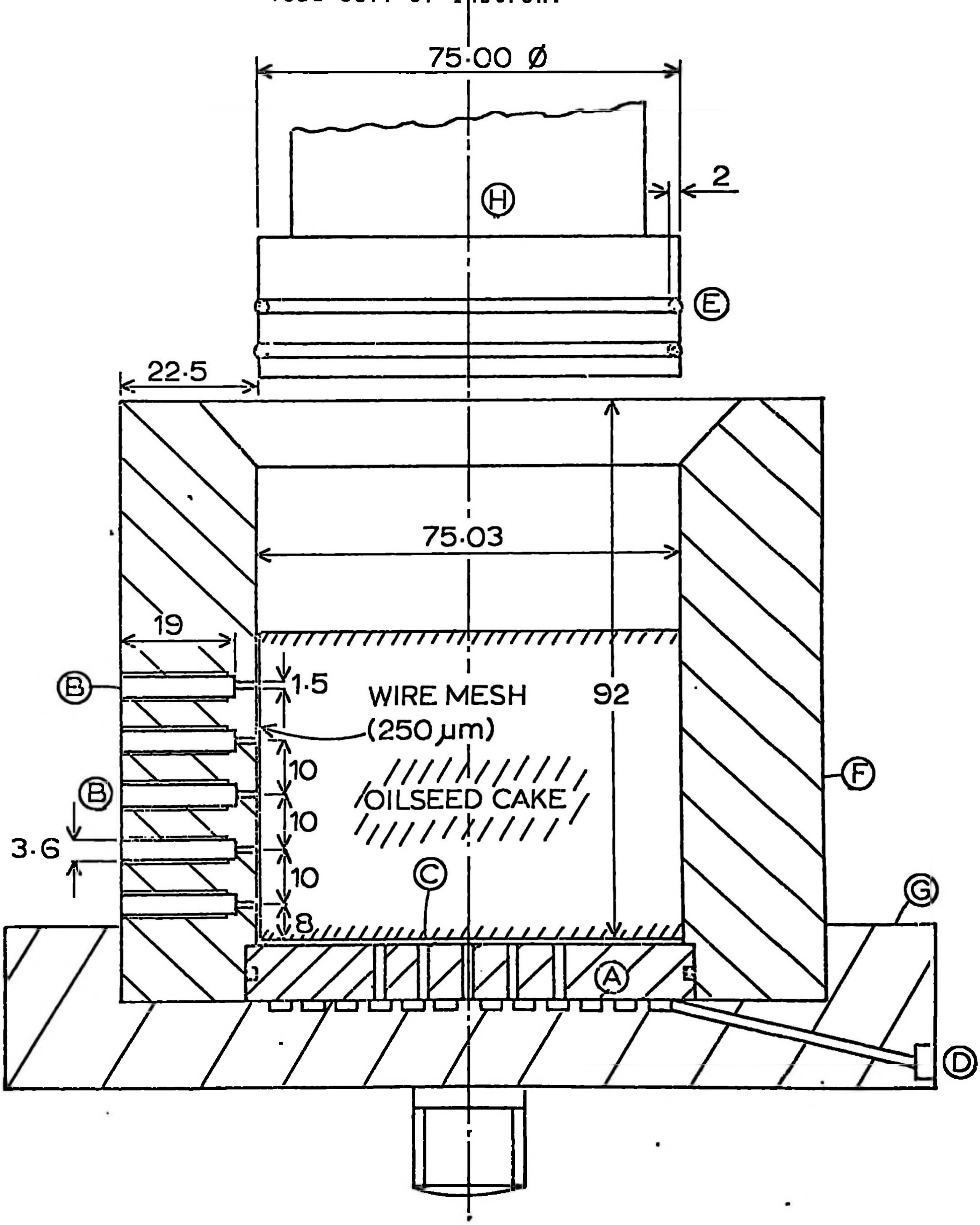
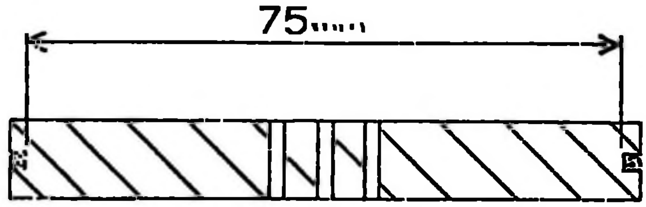
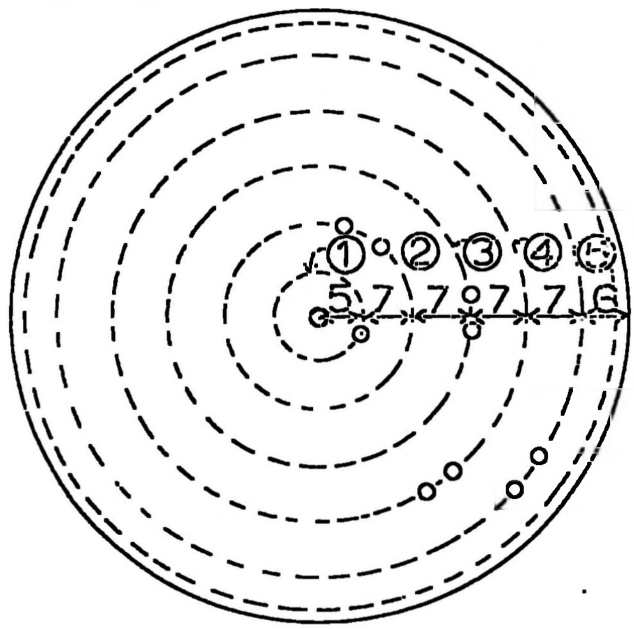


FIG. 16: POROUS DISCS AT BASE OF CYLINDER FOR OIL EXPRESSION RIG (FIG. 16)





2 mm holes in Circles 1 - 5 at approximately 6 mm distance apart, 6 porous discs used:

		D.A.
Disc 1:	Central hole + 3 holes in Circle (1) -	0.28%
Dics 2:	Central hole + 5 holes in Circle (1) -	0.64%
Disc 3:	As in Disc 2 + 8 holes in Circle (2) -	1.85%
Disc 4:	As in Disc 3 + 17 holes in Circle 3 -	3.6%
Disc 5:	As in Disc 4 + 24 holes in Circle 4 -	5.7%
Disc 6:	As in Disc 5 + 30 holes in Circle 5 -	8.25%

D.A. = Drainage Areas as a % of Total cylinder area.

rate of oil expression. The basin is covered by a mild steel porous disc (Fig. 16) capable of carrying the loads used in these tests. Different porous discs were used with different drainage areas varying from 0.28% to 8.3% of the total area to test the effect of varying the drainage area on oil expression. On top of this porous disc two layers of a pair of wire mesh) were placed to stop any solid extrusion with the oil. The cylinder was screwed to the actuator of the Instron whereas the plunger was screwed to the load cell attached to the stationary crosshead. On the side of the cylinder there were a series of 3.6 mm diameter holes for attachment of pressure transducers (Kulite XTM - 190 pressure transducers - pressure range 0 - 20 MPa) for measuring the pore/fluid pressure of the oil as it is being expressed. The pore/fluid pressure transducers were connected to a multi-channel X - Y recorder (Phillips multi-channel recorder type 9404 372 001 Serial No. 6301 range 0 - 200 mV).

3.3.2. EXPERIMENTAL PROCEDURE AND RESULTS.

In each test 200 g of oil seed was used which filled the cylinder. Due to limitations of the Instron 1274 UTM in that the maximum amplitude of the actuator is 50 mm while the stroke of the plunger/cylinder rig is 92 mm it was necessary to pre-press the seeds initially to reduce the height. A uniform level of pre-pressing was obtained by loading until oil expression commenced.

3.3.2.1 Determination of load at which oil expression commenced.

(a) Procedure: To determine the pressure and volume of the seeds at the point when oil expression commenced several undrained testswere conducted using a non-porous disc at the base of cylinder. The second pore pressure hole from the bottom was left open with the seeds in a wire mesh and pressing commenced at a constant speed of 5 mm/min until oil was observed to flow out at the open point. The Instron was then stopped and the load at which oil expression begun was noted from the digital readout of the Instron as this gave a more accurate reading than the strip-chart recordings. The volume of the seeds at this point was calculated from the strip-chart recordings.

(b) Results: Typical load -distance curves for the initial pressing are shown in Fig. 17 whereas Table 4 shows the average value of five tests for the pressure, volume and density at the point when oil expression commenced.

The volume was calculated by multiplying the area of the cylinder (4418.44 mm) by the difference between the full stroke of the cylinder from zero position (92 mm) and the distance moved by the plunger

FIG. 17: TYPICAL CURVES FOR THE INITIAL PRESSING OF RAPESEED AND CASHEW TO DETERMINE LOAD AT WHICH OIL EXPRESSION COMMENCES.

Initial Height = 92 nm, a = Load at which oil expression commences.
Area of cylinder = 4418.44 nm^2 Mass of oilseeds = 200g.

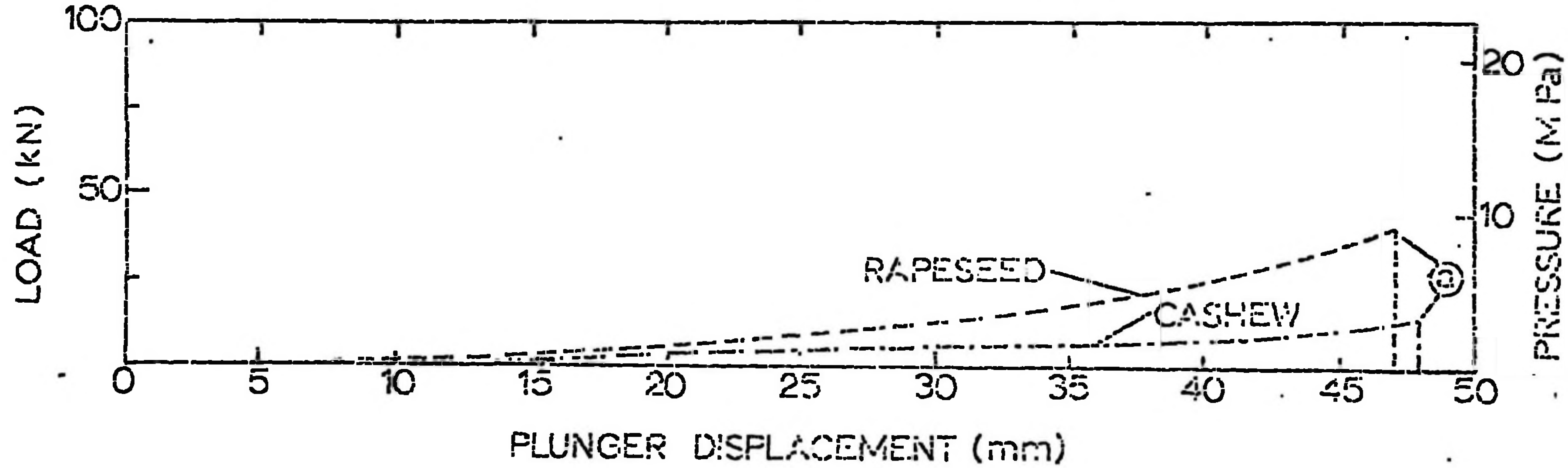


TABLE 4: PRESSURE, VOLUME AND DENSITY AT WHICH OIL EXPRESSION COMMENCES.

Loaded at constant rate of strain of 5 mm/min until oil expression commenced. Disc at base of cylinder non-porous. One pore pressure hole left open.

Oilseed	Pressure (MPa)	Volume (ml)	Density kg/m ^{3}
Cashew	3.37 ± 0.07	198.9 ± 1.14	1005.5
Rapeseed	9.06 ± 0.06	201.3 ± 0.92	993.5

± Standard Error

n = 5 tests in each case.

during a test. The density was obtained by dividinq the weight (200g) with the volume obtained. As it will be shown later (section 3.3.2.6) the volume figures are higher than the air free volume of rapeseed and cashew indicating the presence of air in the oilseed cake when oil expression commences. In all the tests in this series the seeds were pre-pressed to a load of 3.37 MPa for cashew and 9.05 MPa for rapeseed.

3.3.2.2. Effect of varying the rate of loading.

(a) Procedure: The rate of loading was varied from 62.9 kPa/s to 377.2 kPa/s. The load was raised from zero to 56.6 MPa and then held there until 1950s. At this time the rate of expression was quite small. All the tests were done at ambient temperature. The rate at which the oil was being expressed was measured in a 25 ml graduated cylinder at time intervals of 30s in the first 240s when the rate of oil expression was high and 120s during the remaining period. Change in height of the oil seeds was recorded on the strip-chart recorder.

(b) Results: Typical data of change in height of the oilseed cake with time (and therefore α oil expressed) are shown in Fig. 18. The change in height (and oil expressed) increases rapidly at short times and slowly at longer times. Thus the effect of time is significant only in the first 600s. Previous work by among others Koo,(1942) Baskerville et al (1947).

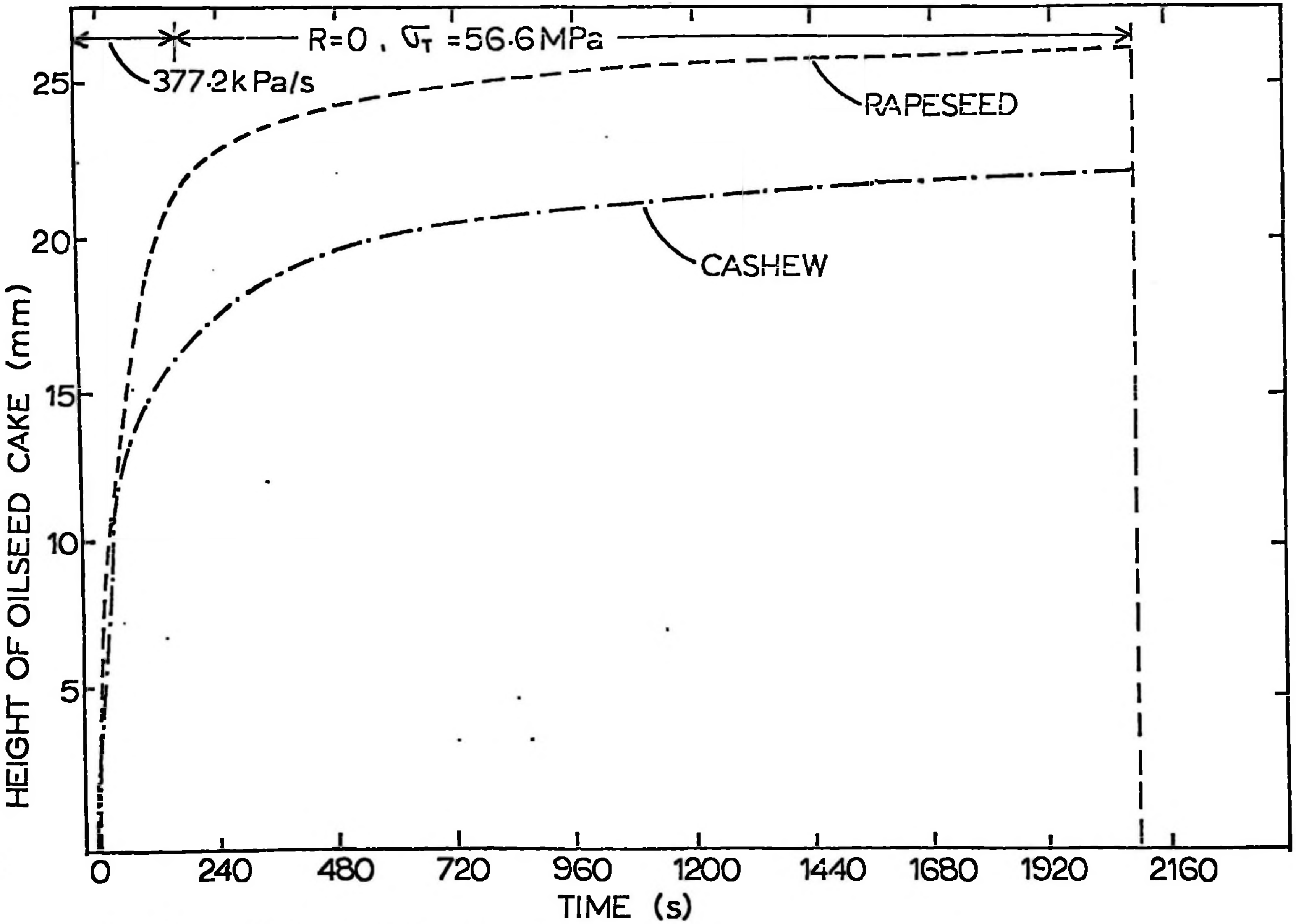


FIG. 18: TYPICAL CURVES FOR CHANCE IN HEIGHT OF CASHEW AND RAPESEED.

(200g each case).

concentrated at times in excess of 1800s where the effect of time is insignificant. The curves for change in volume of the oilseeds during oil expression are similar to curves obtained in the consolidation of soils (Taylor, 1966; Biot, 1941; Terzaghi, 1943). The change in volume of the oilseeds during expression was in all cases greater than the oil expressed (Fig.19) The difference between the two curves indicated the presence of air which is either dissolved in the oil or compressed during expression. At times greater than 1950s the air volume was calculated as 20% and 14% of the air frec volume, in rapeseed and cashew respectively (Table 5). The effect of this air on oil expression is discussed in section 3.3.2.6.

The effect of varying the initial rate of loading on oil expression is shown in Fig. 20 . It is seen that varying the initial rate of loading has little effect on the final amount of oil expressed as long as the net duration of loading is the same for each case. However, this is so only when the drainage area is greater than 0.64% as will be shown in section 3.3.2.3. In all cases over 70% of the oil expressed is expressed in the first 600s and the rate at which the oil is expressed decreases until at times in excess of 1200s the rate of expression is quite low. Carter (1953) had recommended that there was little advantage to be gained in pressing cottonseed longer than 2100s,

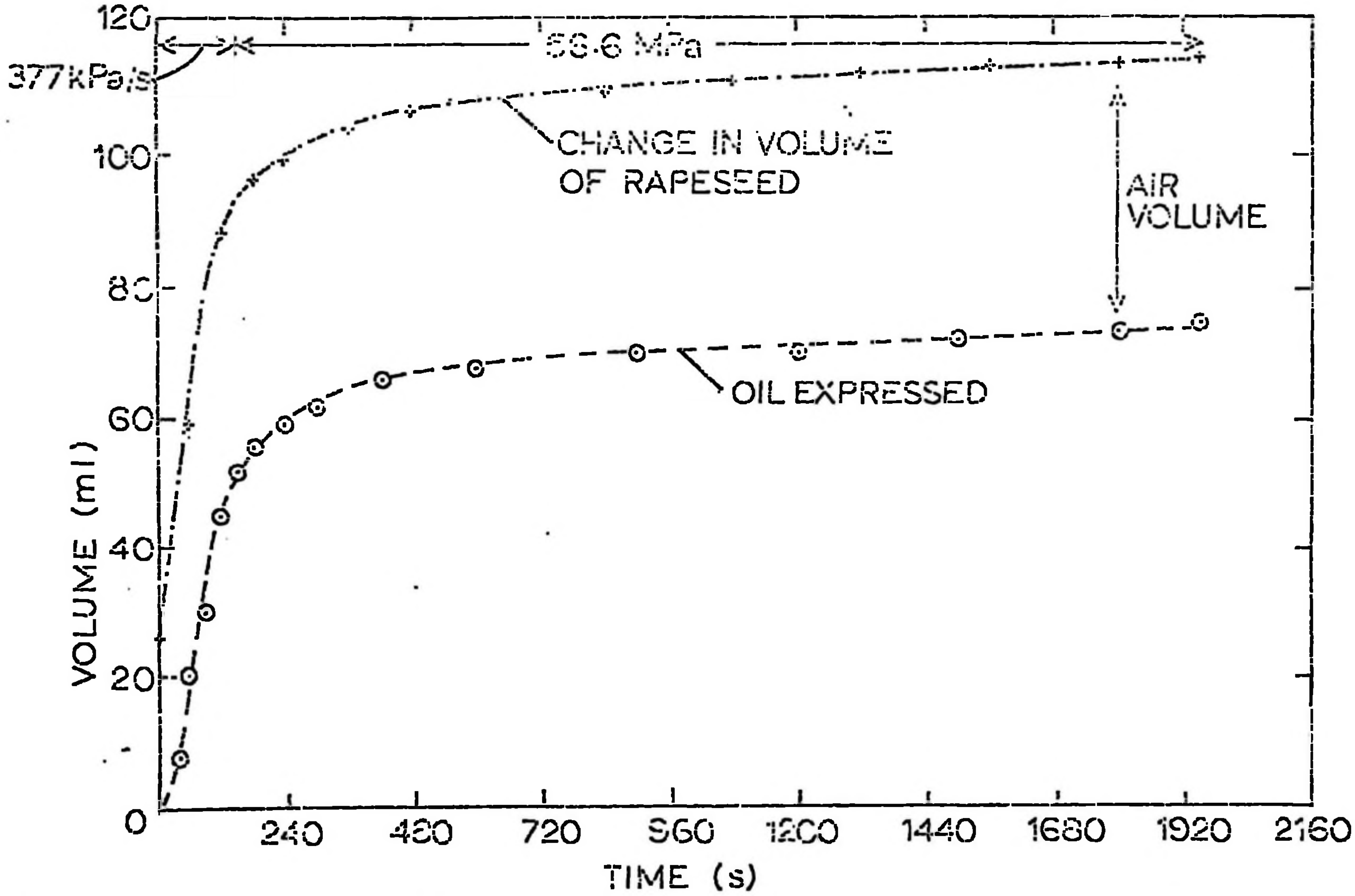


FIG. 19: COMPARISON BETWEEN CHANGE IN VOLUME OF OILSEED CAKE AND VOLUME OF OIL EXPRESSED FOR RAPESEED.

(200 g of rapeseed ; Drainage area 0.64%)

TABLE 5: COMPARISON BETWEEN CHANGE IN VOLUME OF OILSEEDS AND VOLUME OF OIL EXPRESSED.

V_s = Volume of oilseeds after pressing for 1 hour

V_0 = Volume of oil expressed after pressing for 1 hour.

R = Rate of loading.

V_{af} = Air free volume obtained as in section 3.3.2.6.

R kPa/s	V_s (ml)	V_0 (ml)	$\frac{V_s - V_0}{V_{af}} \times 100$ %
RAPESEED: V_{af} = 182.8 ml.			
377	114.9	76.5	20.8
189	112.3	73.0	21.5
94	108.3	73.0	19.3
63	112.7	76.0	20.1
		AVERAGE	= 20.4%
CASHEW: V_{af} = 180.8 ml.			
377	98.5	76.0	12.4
189	106.0	76.5	16.3
94	99.4	76.0	13.5
63	105.2	75.0	16.7
		AVERAGE	= 14.7%

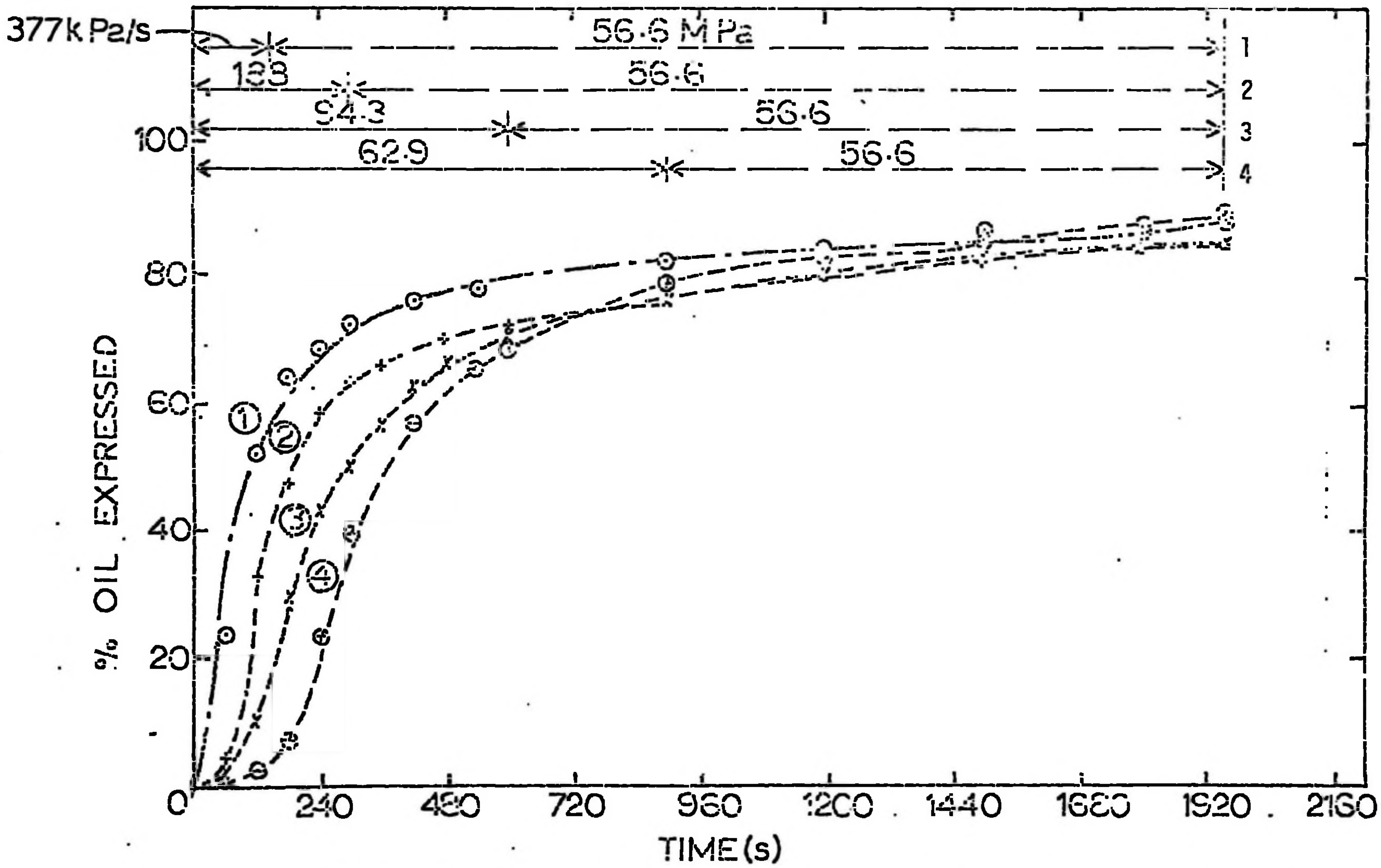


FIG. 20: EFFECT OF VARYING THE RATE OF LOADING (R) ON OIL EXPRESSION FOR RAPESEED.

Drainage Area 0.64% rates of loading 1 - 4 and oil expressed 1 - 4.

however, all empirical models reviewed earlier were based on data in excess of 1800s.

Also even though thefinal amount of oil expressed.is the same, less oil is expressed in the first 240s for the lower rates of loading than in the higher rates of loading. (eg. 23% oil was expressed in the initial 240s for a loading rate of 62.9 kPa/s compared to 68% during the same period for a rate of loading of 377.2 kPa/s for rapeseed). The explanation for this phenomena is presented in Chapter 6.

The results presented in this section are for one drainage area (0.64% of total cylinder area). In the next section (3.3.2.3) the effect of varying the drainage area will be considered.

3.3.2.3: Effect of varying drainage area on oil expression.

(a) Procedure: Different porous discs at the base of the cylinder (Fig. 16) were used to determine the effect of varying the drainage area on oil expression and fluid/pore pressure in the oil. The expression procedure was as outlined in section 3.3.2.2 (a) i.e. initially pre-pressing until a load of 3.37 MPa and 9.054 MPa for cashew and rapeseed respectively and then final expression using initial rates of loading varying from 62.9 kPa/s to 377.2 kPa/s until a load of 56.6 MPa which was then maintained for the rest of the expression time.

(b) Results: The effect of varying the drainage area for 1 loading rate is shown in Fig. 21 for rapeseed while Table 6 and 7 shows the same effect for various loading rates and for rapeseed and cashew respectively. The data in Fig. 21 and Tables 6 and 7 reveal that decreasing the drainage area from 8.3% to 0.64% leads to an increase in the amount of oil expressed. For example for a drainage area of 8.3% and a loading rate of 62.8 kPa/s the oil expressed at 1800s was 25.1% while for a drainage area of 0.64% the oil expressed during the same period was 72.5% for rapeseed (Table 6 and Fig. 21). Decreasing the drainage area further than 0.64% led to a decrease in the amount of oil expressed. For example for

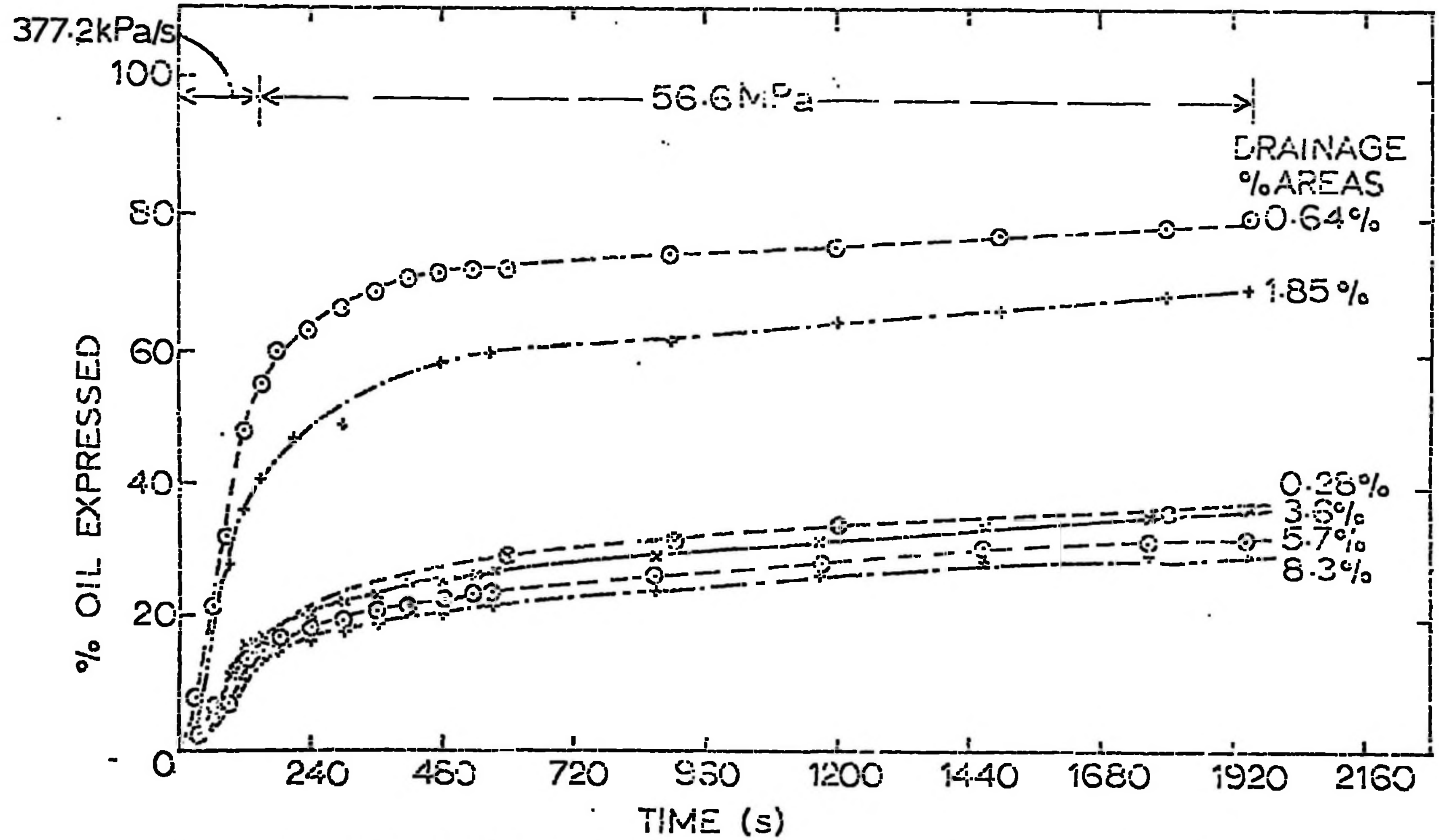


FIG. 21: EFFECT OF VARYING DRAINAGE AREA ON OIL EXPRESSION FOR RAPESEED.

(Drainage areas as in Fig. 16, Loading rate 377.2 kPa/s until 56.6 MPa and then hold).

TABLE 6: % OIL EXPRESSED FOR RAPESEED AT DIFFERENT TIMES, LOADING RATES AND DRAINAGE AREAS

R = Rate of loading (kPa/s), A_d = % drainage area (% of total cylinder Area)

t = time (s)

R → / A_d ↓	377.2 kPa/s					188.2kPa/s					94.3 kPa/s					62.8 kPa/s				
t →	60	150	240	600	1800	60	120	300	900	1800	60	120	300	600	1800	60	300	900	1200	1800
0.28%	6.8	16.1	21.0	28.1	35.7	5.1	15.8	22.7	30.7	37.2	1.7	2.9	21.2	32.7	42.0	0	23.5	42.6	45.1	48.0
0.64%	21.3	51.5	62.9	72.5	78.4	4.8	29.9	57.6	70.4	77.3	0	9.6	45.8	64.0	77.3	0	36.3	72.5	75.2	80.0
1.85%	20.3	40.5	48.0	60.0	68.8	3.6	8.9	44.6	59.3	65.2	0	9.8	34.6	51.3	62.8	0	33.4	56.8	60.7	63.2
3.60%	6.4	17.1	20.8	27.5	35.3	3.4	6.7	21.7	29.2	35.1	0	6.4	21.4	28.0	35.7	0	24.3	30.0	31.0	32.4
5.70%	5.3	14.9	18.7	24.2	31.5	3.0	6.4	17.0	26.4	31.5	0	5.2	16.8	26.3	32.0	0	21.3	26.3	27.6	29.8
8.30%	4.7	12.6	17.0	21.0	29.5	2.8	5.3	15.2	24.7	29.0	0	3.2	10.0	20.8	28.1	0	18.2	26.0	26.4	27.3

TABLE 7: % OIL EXPRESSED FOR CASHEW AT DIFFERENT TIMES, LOADING RATES AND DRAINAGE.

R = Rate of loading Initially (kPa/s). A_d = % drainage area (% of total cylinder Area. t = time (s)

R → / A_d ↓	377.2 kPa/s					188.2 kPa/s					94.3 kPa/s					62.8 kPa/s				
t →	60	150	240	600	1800	60	120	300	900	1800	60	120	300	600	1800	60	300	900	1200	1800
0.64%	21.2	57.7	65.4	69.7	76.3	5.6	31.2	55.2	76.2	79.2	2.7	21.4	47.9	71.1	779.6	1.1	38.1	75.2	79.0	82.2
1,85%	22.1	50.1	52.7	59.2	66.4	4.9	16.2	47.6	62.4	66.3	2.9	9.8	36.2	56.0	63.7	0	32.7	57.3	61.2	64.3
3.60%	7.8	19.3	23.2	29.6	38.9	3.9	11.2	26.4	29.6	34.7	2.5	8.7	22.4	34.3	36.7	0	20.1	30.3	31.2	33.5
5.70%	4.8	17.4	19.1	28.2	31.8	3.2	9.2	21.3	28.0	32.4	2.2	7.1	17.2	27.2	32.9	0	18.0	27.2	28.0	30.2
8.30%	3.8	13.0	17.2	27.2	30.9	3.2	8.2	17.0	26.8	29.9	0	4.5	11.2	22.1	28.3	0	16.1	24.0	25.0	28.1

a loading rate of 62.9 kPa/s the amount of oil expressed for a drainage area of 0.28% was 48% at 1800s for rapeseed (Table 6). Increasing the initial rate of loading decreased further the amount of oil expressed (e.g only 35.7% was expressed for a drainage area 0.28% and loading rate of 377.2 kPa/s). The effect of varying the % drainage area on oil expressed at 1800s for 2 loading rates (377.2 kPa/s and 62.8 kPa/s) are shown in Fig. 22. Fig. 22 reveals that as the drainage area increases the % oil expressed increases and then decreases. The largest amount of oil is expressed with drainage areas between 0.5 to 1.5%. When the drainage area is increased to more than 4% it's effect on the amount of oil expressed is minimal. The effect of varying the drainage area does not appear to have been studied in expression of oil or other agricultural products. In screw expellers the drainage areas vary from 2% to 6% depending on the type of seed being pressed (Norris (1964), Ward (1976)). For example for small seeds such as rapeseed, cottonseed, the drainage area is about 2% while for large and fibrous seeds such as copra the drainage area is about 6%, the selection criteria being the filtering capability of drainage area rather than the amount of oil expressed. In soil consolidation tests standard porous stones are used which according to B.S. 1377:1975.

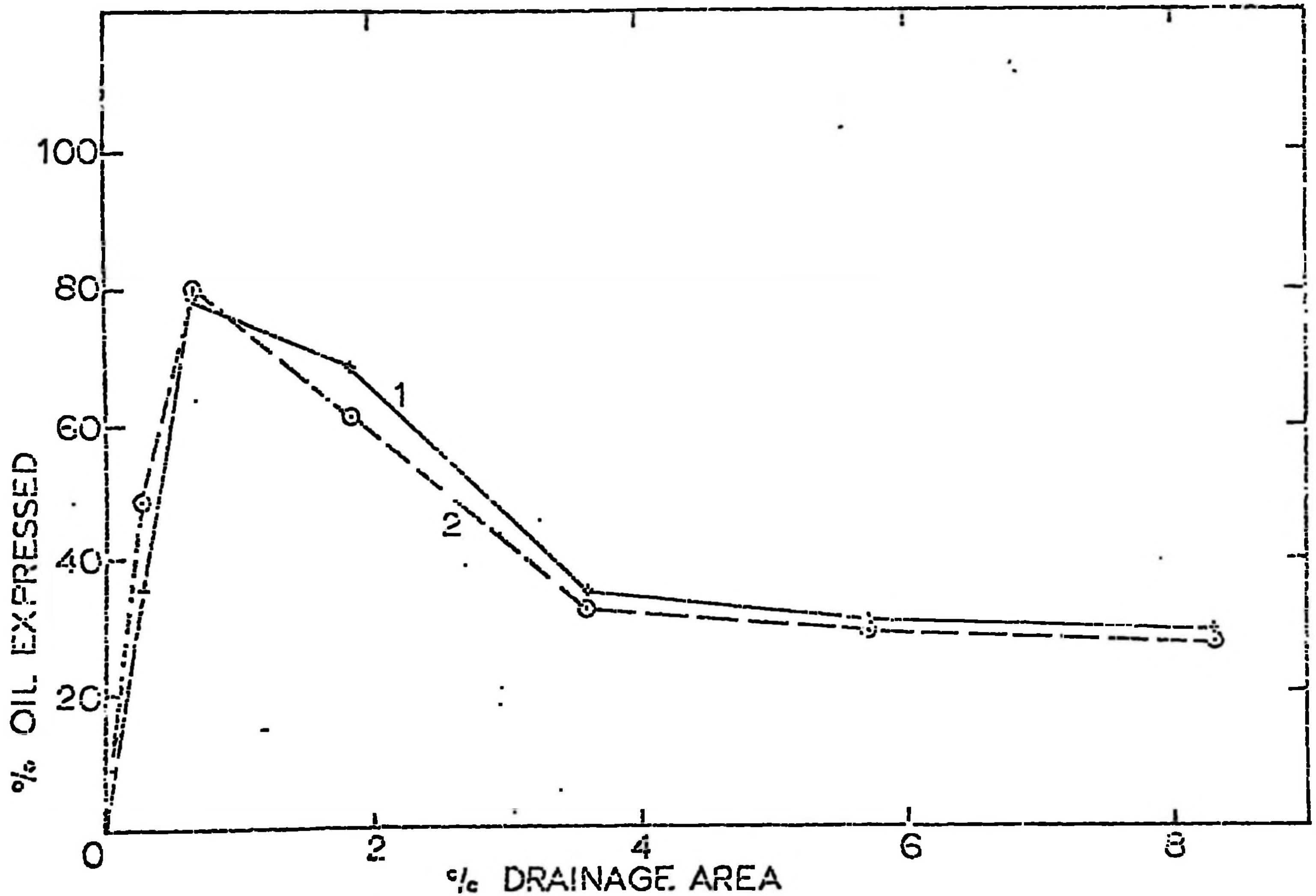


FIG. 22: EFFECT OF DRAINAGE AREA AND LOADING RATE ON OIL EXPRESSED AT 1800s.

1 - Initial loading rate of 377.2 kPa/s until 56.6 MPa and hold until 1920s
2 - Initial loading rate of 62.9 kPa/s until 56.6 MPa and hold until 1920s.

> "The porous plates should permit free drainage of the specimen at all stages of consolidation. They should also be able to withstand the maximum vertical axial consolidation pressure applied to the soil specimen; plates of sintered fused aluminium oxide 6 mm to 13 mm thick and sintered bronze 3 mm thick have been found adequate"

However there have been attempts to study the effect of increasing the drainage path in soil consolidation which is affected when the drainage area is changed and this will be discussed more fully in Chapter 6.

These results show that the drainage areas is an important parameter in the expression process.

3.3.3.4. Fluid pressure measurement:

(a) Procedure: For measuring the pressure of the oil during expression or during undrained compression a wire mesh (stainless steel 250 µm) was placed inside the cylinder on the walls to prevent extrusion of solids into the pore pressure holes (1.5 mm diameter). Thus only oil could reach the pressure transducers. Kulite XTM 190 pressure transducers were inserted after the initial pre-pressing as described in section 3.2.3.1. The pressure was recorded on Phillips X - Y recorder. (cf. Details in Appendix 2).

(b) Results: Typical X - Y recording of the fluid/pore pressure as the oil is being expressed at a point 18 mm from the base of the oilseed cake is shown in Fig. 23. Fig. 23 shows that the fluid/pore pressure increases linearly when the applied pressure is being increased (first 2.5 minutes) and when the applied pressure is maintained constant there is a decrease in the fluid pressure. It has been shown in sections 3.3.3.2 and 3.3.3.3 that a substantial part of the oil expressed is expressed during the first 150s. In expressing this oil, some of the fluid pressure must be dissipated in overcoming the resistance to oil flow through the oilseed cake. Therefore during this initial period when the applied pressure is increasing the transducer is measuring the resultant fluid pressure.

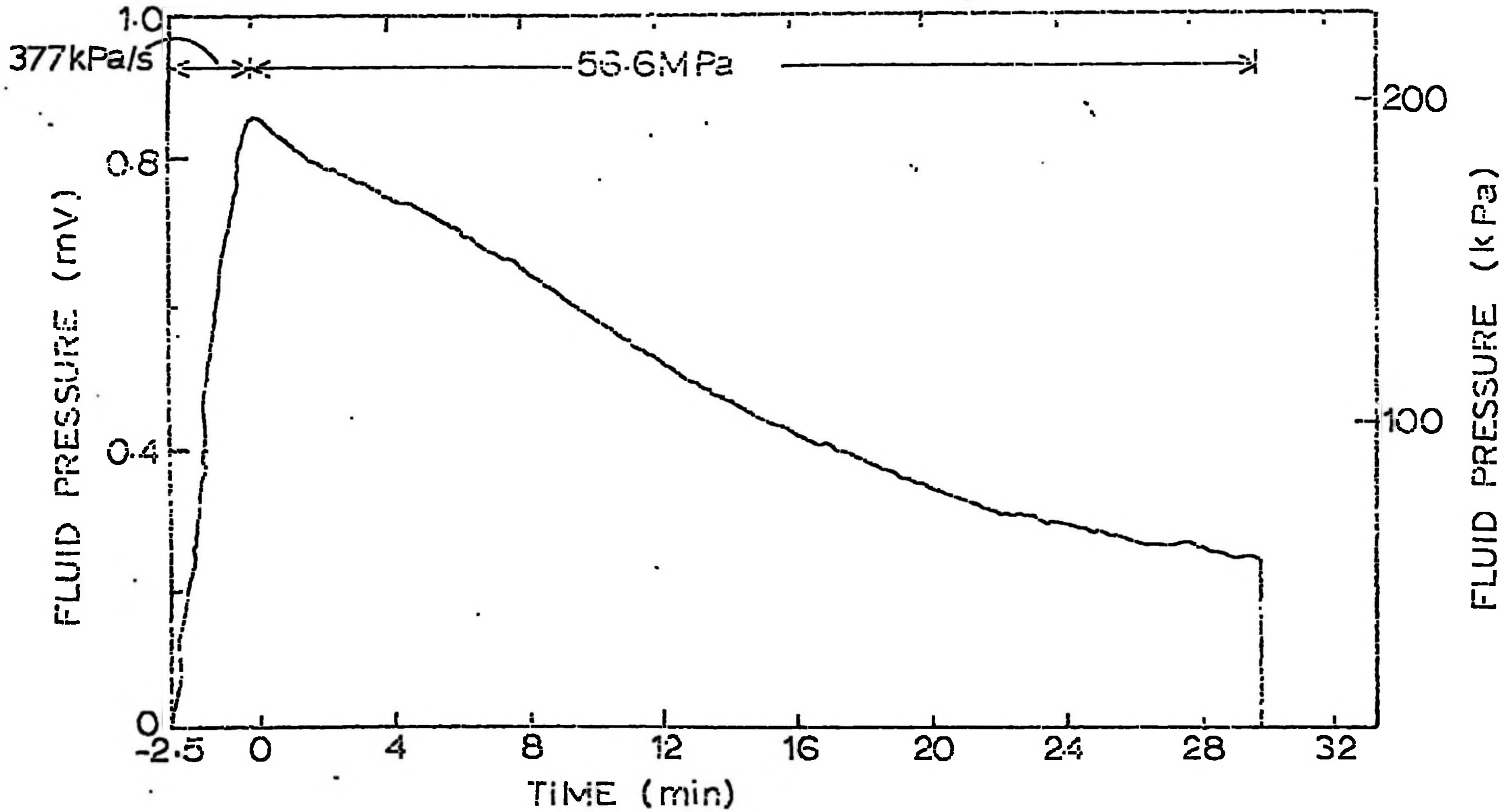


FIG. 23 TYPICAL X - Y RECORDING OF INTRA KERNEL PORE PRESSURE IN RAPESEED.

z = 18 mm from base of cylinder. Drainage area = 0.64%
0.03 mV = 6.895 kPa. Loading rate 377.2 kPa/s. Constant load period from Time zero.

The true fluid pressure will be the fluid pressure measured plus the dissipated fluid pressure. When the applied pressure is constant the transducer is measuring the rate of decrease (or dissipation) of the fluid pressure.

The ratio of fluid pressure to applied pressure is quite low in oilseeds in comparison to what is common in the consolidation of soils (equation 6). For example in oilseeds the maximum fluid pressure when σ = 56.6 MPa was 197.2 kPa i.e. u = 0.4% of σ_T whereas in soil consolidation u $\simeq$ 20% of σ_T . It was initially thought that this was due to the presence of air in the oilseeds. However, as will be discussed in section 3.3.3.6.the air present appears to be dissolved in the oil and this deviation is due to structural differences between oilseeds and soils.

The consolidation process in soils is governed by the partial differential equation 8. In the case where the applied load is applied instanteously (i.e. σ_1 is constant and hence $\partial\sigma_1/\partial t = 0$) equation 8 reduces to the commonly encountered equation of diffusion (equation (9) - ($(C_v \partial^2 u/\partial z^2)$) = $\partial u/\partial t$). This equation has been solved for consolidation of soils for various initial and boundary conditions. The initial and boundary conditions of the expression rig are:

$$u = 0 \text{ at } z = 0 \quad \text{(exit point of oil).}$$

and at $z = h$ (top of seedcake) $\partial u/\partial z = 0$ (no drainage)

and

and at $t = 0$ initial height is $= H$.

The solution to equation (9) with these conditions is:

$$u = (4u_0/\pi)(((\exp(-M_1 t))(\mathrm{Sin}(\pi z/H))+((\exp(-9M_1 t))(\mathrm{Sin}(3\pi z/H))) +..$$
$$+.........+.......+.......)$$

where u = initial fluid/pore pressure which for soils is taken as equal to the applied pressure. (σ_T) and u = Initial pore pressure.

M_1 = A constant given by $= \pi C_v/H^2$ for soils.

If z is fixed i.e. the fluid pressure is measured at one point, then Sin ($\pi z/H$) = constant, and by ignoring second order terms, equation (16) reduces to:

$$u = M_2(\exp(-M_1 t))$$

where $M_2 = (4u\ /\pi)(\mathrm{Sin}(\pi z/H))$

and taking logs of both sides

$$\ln(u) = M_3 - M_1 t$$

Where $M_3 = \ln(M_2)$ (17)

Therefore a plot of u vs t on semi-log paper should yield an approximate straight line when σ_T = constant suggesting the dissipation of fluid pressure during this period is an exponential function of time.

Experimental data of fluid pressure (u) against time were plotted on a semi-log paper to determine if the dissipation of fluid pressure in oilseeds when applied load is constant is an exponential function of time. Fig. 24 is a typical plot of u vs t on semi-log scale for rapeseed for 5 drainage areas. Similar results were obtained for cashew. The results of the equation (17) are summarised in Table 8.

The fluid pressure increased with a decrease in drainage area. This will partly explain why there was more oil expressed in the tests when the drainage area was small i.e. the driving force - pressure potential is higher in the smaller drainage areas. The slope of the ln u vs t plot is almost the same for all the drainage areas (Table 8). The fluid pressure decreased with a decrease in height z - (i.e. fluid pressure was lower at points near the exit.) Fig. 25 shows the fluid pressure measured at three points z = 8, 18, 28 mm from the cylinder base simultaneously revealing that the fluid pressure increases as cake height increases. The pore pressure in soils during consolidation increases in a similar way although it is a much higher fraction of the applied pressure compared to pore pressure in oilseeds.

FIG. 24: PLOTS OF LOG U - t FOR RAPESEED WHEN APPLIED PRESSURE (σ) = CONSTANT EQUATION 17) FOR VARIOUS DRAINAGE AREAS.

Initial loading rate R = 377.2 kPa/s.

σ_T = 56.6 MPa, (1) is plot of u from Fig.23 when t >0.

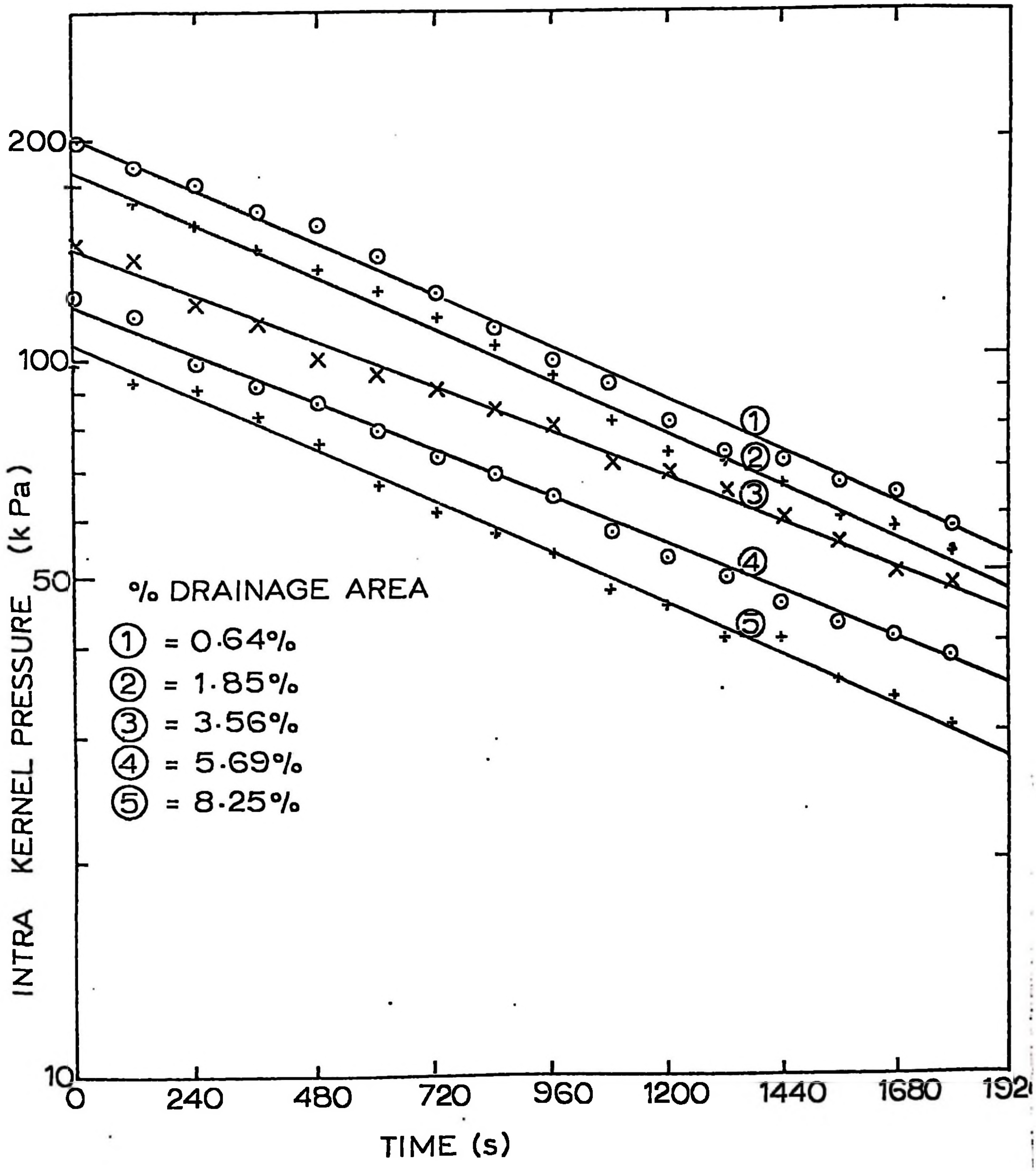


TABLE 8: VALUES OF CONSTANTS M_1 AND M_3 IN EQUATION (17)

Equation 17:- $\ln(u) = M_3 - M_1 t$ Pore pressure u measured at z = 18 mm from base of cylinder.

Drainage area %	RAPESEED		CASHEW	
	M_1	M_3	M_1	M_3
0.57%	+ 7.0×10^{-4}	5.30	7.4×10^{-4}	5.44
1.85%	6.4×10^{-4}	5.16	6.7×10^{-4}	5.21
3.56%	6.0×10^{-4}	4.96	7.3×10^{-4}	5.12
5.69%	6.5×10^{-4}	4.80	6.6×10^{-4}	4.89
8.25%	8.5×10^{-4}	4.95	7.0×10^{-4}	4.65

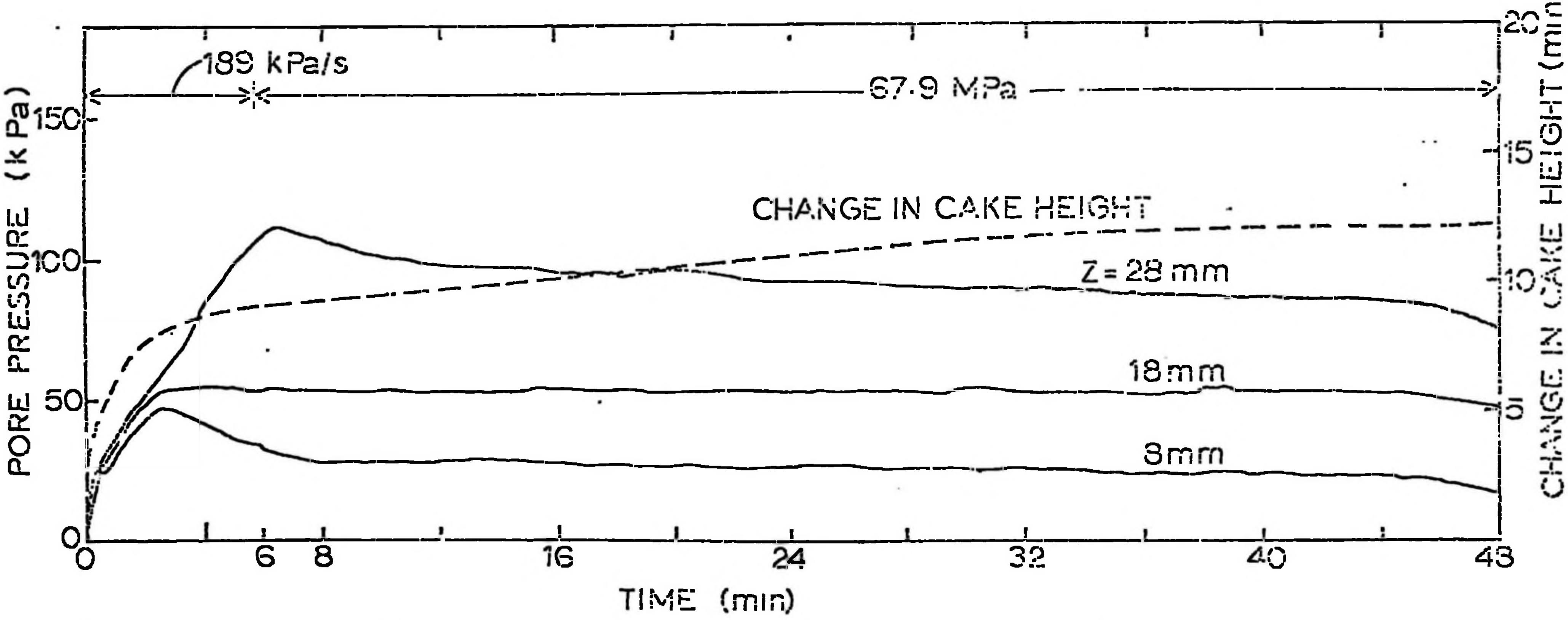


FIG. 25: PORE PRESSURE MEASURED AT THREE POINTS AT HEIGHTS Z = 8, 18, 28 mm FROM BASE OF CYLINDER FOR CASHEW.

Drainage area = 8.25%. Loading rate 189kPa/s until 67.9. MPa.

The results in this section show that there is some analogy between the consolidation process in soils and expression process in oilseeds in that:-

- there is a fluid pressure which when the applied pressure is constant is an exponential function of time as in consolidation of soils.

- the fluid pressure decreases as the exit point of the oil from the cake is approached, and hence indicating equi-potential lines in the oilseed cake.

However the ratio of the fluid pressure to the applied pressure in oilseeds is very low compared to that common to soils. The consolidation process is modelled on the spring analogy shown in Fig. 2 (Chapter 2). This dictates that the applied pressure is divided into two parts during drained compression of saturated soils as in equation (6) and the applied pressure is entirely carried by the liquid phase during undrained compression ($u=\sigma_T$). It is necessary therefore to check the behaviour of oilseeds during undrained compression to determine the extent of applicability of the soil consolidation principles to the expression process.

3.3.5 Undrained compression of oilseeds.

(a) Procedure: The porous disc at the base of the cylinder was replaced by an non-porous disc and a wire mesh was placed around the inside wall of the cylinder with one of the pore pressure holes open. The oilseeds after being placed inside the wire mesh in the cylinder were pre-pressed as described in section 3.3.2.1(a) The pressure transducer was then Tnserted into the open hole after resetting of the actuator and pressing commenced.

(b) Results: Typical curves showing the variation of pore pressure, and height of oilseed cake with time for undrained compression of cashew are shown in Fig. 26. The fluid/pore pressure increases linearly as the applied pressure increases likewise but at a slower rate (first 6 minutes in Fig. 26). When the applied pressure is held constant the pore pressure becomes constant at a value of about 25% of the applied pressure. Fig. 27 shows the effect of initiating a leakage in the system (by opening one of the pore pressure holes) during undrained compression. There is a sudden drop in the pore pressure (despite the applied pressure still increasing) and a sudden increases (due to the oil leaking out) of the change in height (axial deformation) of the oilseed cake. The effect of using higher applied pressures during undrained compression for both rapeseed and cashew is shown in

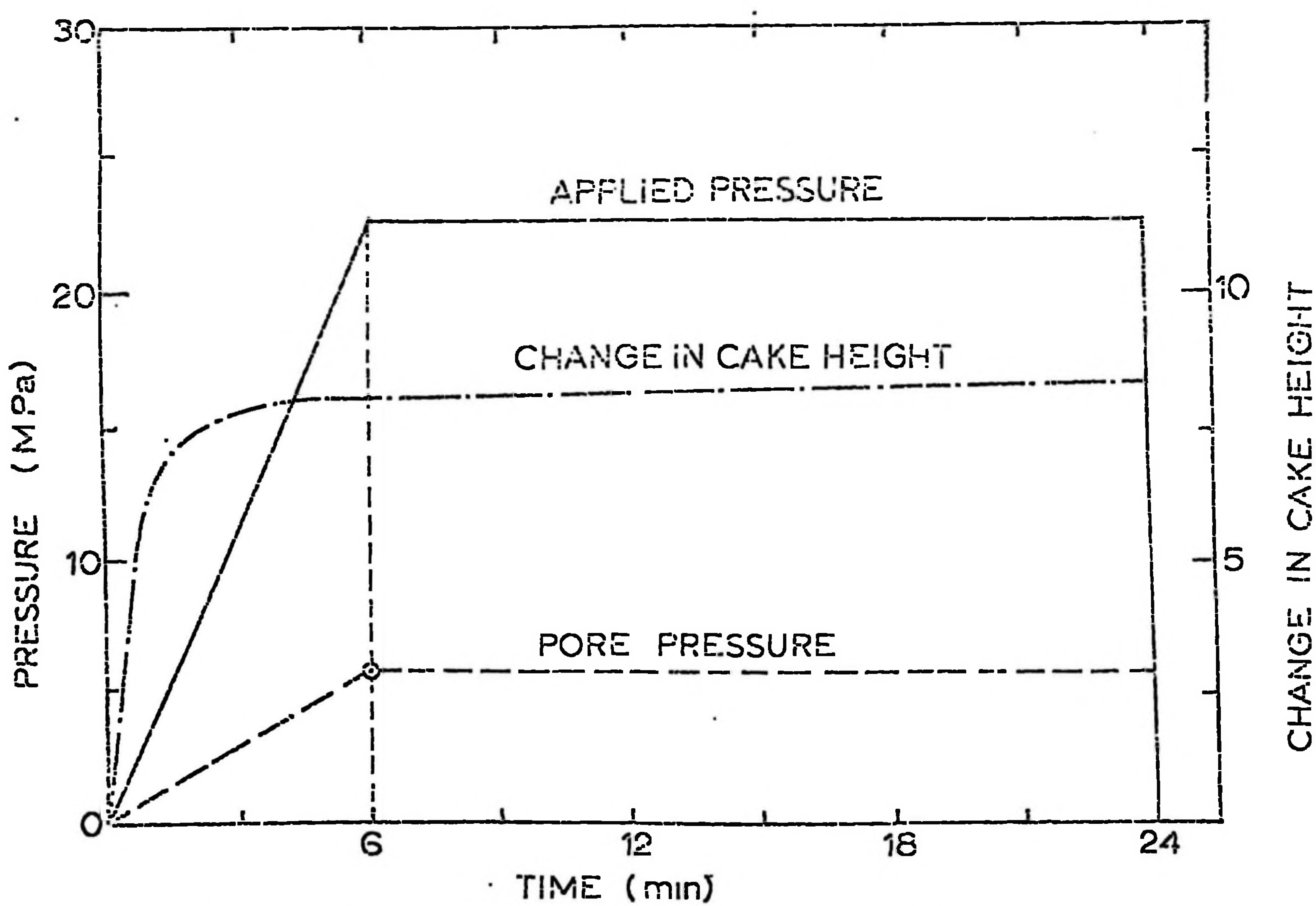


FIG. 26: **VARIATION OF PORE PRESSURE AND CAKE HEIGHT DURING UNDRAINED LAODING AT LOW APPLIED PRESSURES FOR CASHEW:**

Change in cake height (mm). Pore pressure measured at $z = 18$ mm from base of cylinder.

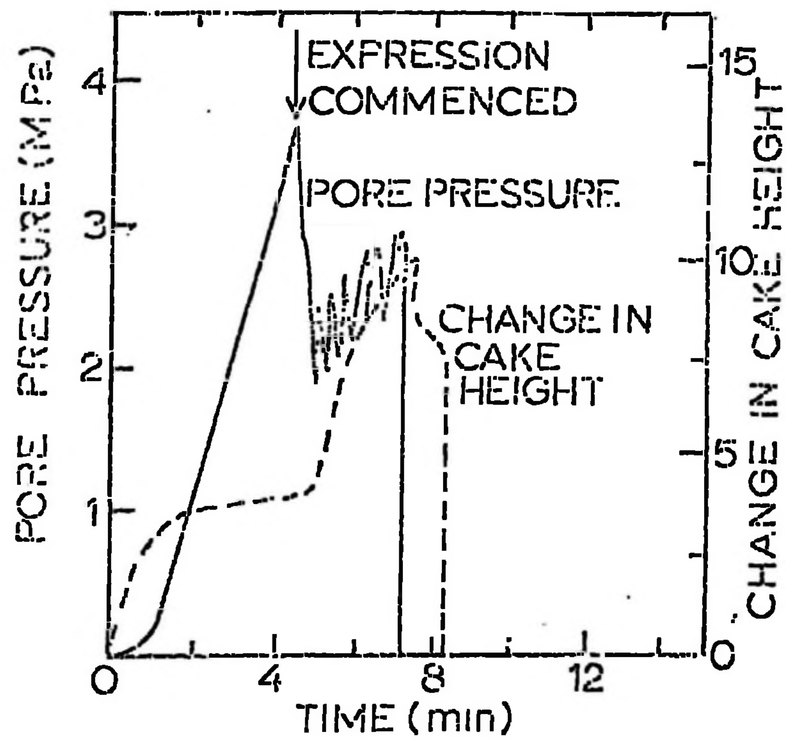


FIG. 27: VARIATION OF PRORE PRESSURE ANC CAKE HEIGHT DURING UNDRAINED COMPRESSION WITH OIL EXPRESSION (LEAKAGE) INITIATED DURING THE COMPRESSION. FOR RAPESEED.

Loading rate 67.8 kPa/s (no holding) pore pressure measured at z = 18 mm from base of cylinder (Fig. 16). Change in cake height in mm.

FIG. 28 PORE PRESSURE FOR RAPESEED AND CASHEW AT HIGH APPLIED PRESSURES DURING UNDRAINED COMPRESSION.

u_c' , u_r' , = cell wall Failure (cf Section 4.4)

σ_{Tc}' , σ_{Tr}' = cell wall Failure (cf Section 4.4)

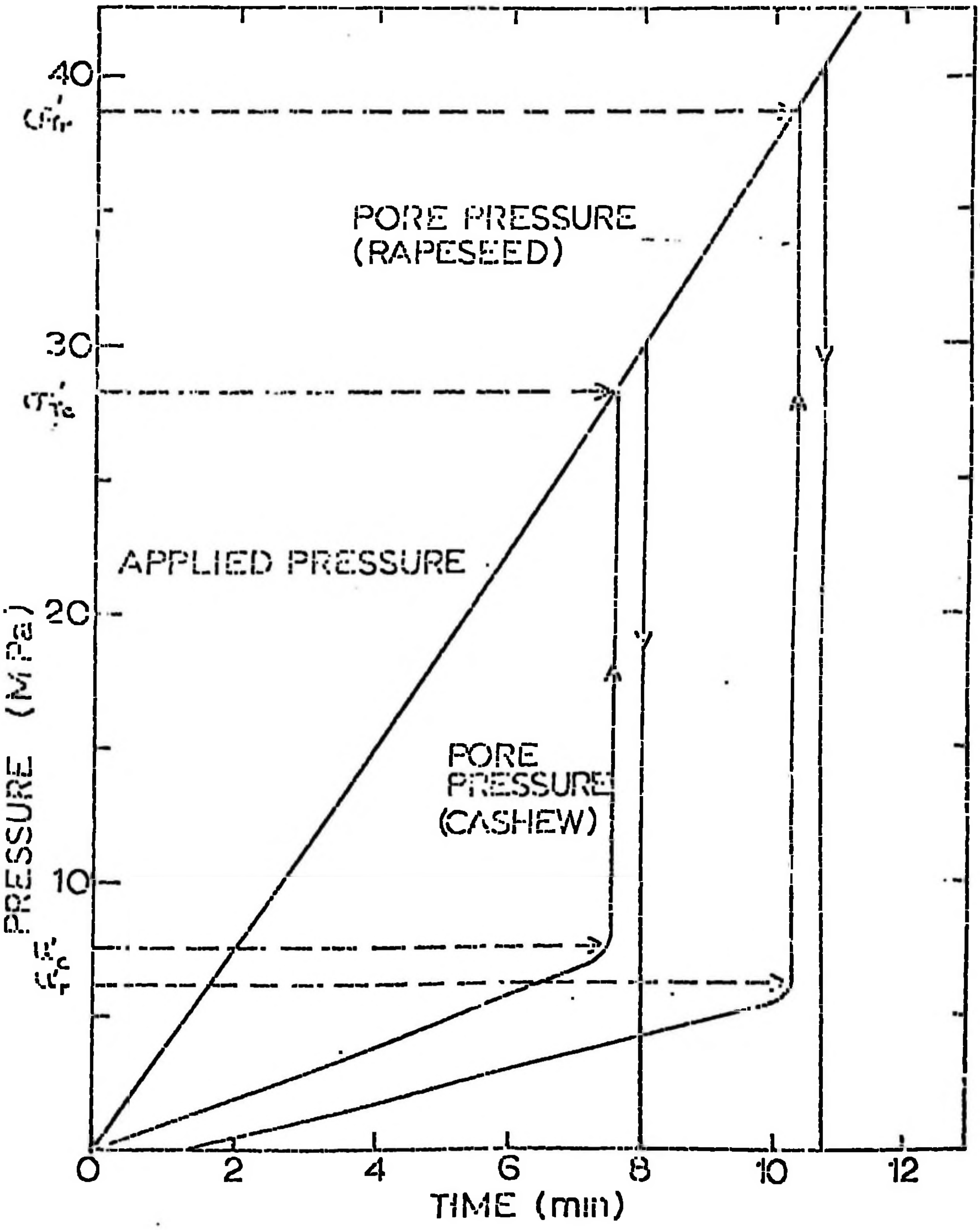


Fig. 28. When the applied pressure was increased to a higher value a pressure is reached (σ_{Tc} = 28.5 for cashew, and σ_{Tr} = 38.7 MPa for rapeseed when there is a steep rise in the fluid pressure until it is equal to the applied pressure (Fig.28).This occurs when the fluid pressure for cashew is u'_c = 7.4 MPa and for rapeseed is u'_r = 6.1 MPa. Microscopic examination of these samples revealed cellwall rupture as will be shown in Chapter 4.

These results show that the oilseeds during undrained compression do not behave the same way as the spring analogy in soil consolidation at low applied pressures. After a particular applied pressure σ_{Tc} and σ_{Tr} for cashew and rapeseed respectively is reached, the oilseeds during undrained compression behaved like soils then.

The deviation from the spring analogy during undrained loading and low pore pressures measured during drained loading could be due to:

(a) Presence of air within the seed kernels and in the intra-kernel voids.

(b) Differences in the microstructure of oilseeds which lead to the expression of oil from them being different from flow of fluids in other porous materials like soils.

The presence of air and it's effect on the expression process has to be studied with reference to the chemical interaction between air and oil i.e. solubility. This is considered in the next section.

3.3.3.6. Effect of trapped air.

(a) Introduction: In Table 5 it was shown that up to 20% of the volume of the oilseeds could be filled with air. In section 3.2.3.6 it was shown that the ratio of the fluid pressure to the applied pressure was quite low in oilseeds compared to other materials such as soils. One of the possible reasons for this could be due to the presence of air in the oilseeds. The air present could be either

(i) within the seed kernel (internal air) or

(ii) external to the seed kernel in the intra-kernel voids.

The internal air could either be trapped between solid tissues or occluded in the oil phase. It is necessary therefore to determine what percentage of the air is in each of the two cases mentioned above.

(b) Determination of the % of internal air:-
The following procedure was used:

(i) The density of whole cashew and rapeseed kernels was determined by displacement method using a specific gravity bottle. Toluene was used which according to Mohsenin (1971) is a better liquid for determining densities of agricultural products in particular those containing fats and oils. An average kernel density of 1.0454 ± 0.0121 (S.E.) g/ml for cashew and 1.0520 ± 0.0173 (SE) g/ml for rapeseed from six determinations each was obtained.

(ii) Rapeseed and cashew kernels were then ground to a fine powder and the oil extracted by the soxhlet method (Official AOAC 1975 methods). Over a five hour extraction period about 99.5% of the oil present can be extracted by this method (AOAC 1975). The extracted cake was then placed in an oven overnight for all petroleum ether to evaporate and moisture to dry out. The density of the cake was determined using the method outlined in (i) above. On addition of toluene to the specific gravity bottle, this was stored for several days with periodic shaking of the bottle to enable any air trapped in the powder to escape. The average density of the solid matter in cashew and rapeseed after five determination each was 1.326 ± 0.0108 g/ml and 1.323 ± 0.013 g/ml (S.E.) respectively (ρ_{sc} , ρ_{sr})

(iii) Since the density of the oil and oil content of the oilseeds is known (section 3.2.3.1), and the moisture content is known, it was possible once the density of the solid matter was known from (ii) above to calculate the air free densities (ρ_{afr} ,ρ_{afr}) of rapeseed and cashew kernels respectively. This was 1.0944 g/cc for rapeseed and 1.106 g/cc for cashew.

(iv) The kernel densities (ρ_{kc} ,ρ_{kr}) are known from (i) and from this the kernel volumes (V_{kc} ,V_{kr} - no intra-kernel air voids) can be calculated. From (iii) the air free densities (ρ_{afr} ,ρ_{afr}) are known and from the air free volumes (V_{afc} ,V_{afr} - No internal and intra-kernel air voids) can be calculated. This was 182.8 and 180.8 ml for 200 g each of rapeseed and cashew respectively. The difference between the kernel volume (V_k) and air free volume (V_{af}) gives the volume of internal air present. This was 5.5% and 3.8% of the air free volume for cashew and rapeseed respectively.

From Table 5 the total % air present was calculated by subtracting the volume of air expressed from total change in volume of the oilseeds when time was large. The average % air present obtained was 14.7 % and 20.4 % of air free volume for cashew and rapeseed respectively.

Of this amount 5.5% and 3.82% is internal air for cashew and rapeseed respectively. This will indicate that there is air between the seed kernels (intra-kernel air voids when oil expression commences (16.6% for rapeseed and 10.9% for cashew).

(c) Effect of intra-kernel air on fluid pressure measurement:-

When oil expression commences the oil will flow into the intra-kernel voids and displace the air. If it is undrained loading the air will be compressed by the oil as it flows out and eventually it will be occluded by the oil as the pressure increases and more oil flows out of the seed kernels into the intra-kernel voids. Oil will dissolve about 4 - 10% of it's own volume of air at atmospheric pressure (Swern, 1964; Murti and Achaya, 1974). The solubility of the main gases in air (Nitrogen and Oxygen) increase considerably with an increase of pressure for most liquids. Markham and Kobe 1941, Frolich et al (1931) and Battino and Clever (1966) have reported that the solubility of oxygen and nitrogen in water and hydrocarbons increase linearly with an increase in pressure. For example the solubility of nitrogen in Iso-propanol increases by about 500% when the pressure is increased from one atmosphere (100kPa) to 40 atmospheres (4.0MPa), while in water the increase is about 150% in the same pressure range. Comparable data on the solubility of air in vegetalbe oils at high pressures are lacking in the literature, however it is reasonable to assume that it will be similar to hydrocarbons. The fluid pressure measured during undrained compression (Fig. 26) was in excess of 5.0 MPa (50 atmospheres). This means therefore than any air present in the intra-kernel voids will dissolve in the oil during undrained compression. It is unlikely therefore that low fluid pressures measured were caused by the presence of air in the intra kernel voids.

(d) Effect of internal air on fluid pressure measurement.

It has been shown that both cashew and rapeseed contain about 3.8% and 5.5% internal air respectively. This air will either be occluded in the oil phase inside the seed kernel or trapped between solid tissues. When pressure is applied during drained or undrained compression the air in oil phase will dissolve in the oil as explained in (c) above. Some of the air trapped between solid tissues will be expressed into the oil where it will dissolve. If the extreme case is taken where it is assumed all the internal air is trapped between the solid tissues and cannot be expressed into the oil phase, then this air will be compressed in accordance with Boyle's law. Thus for 200 gms of oilseeds (cashew):

Initial volume of internal air V_1 = 0.055 X 180.8 = 9.94ml.

Using Boyles law:

Volume after application of pressure P_2 = V_2 = $P_1 V_1/V_2$.

Take P = initial volume = 1 atmosphere = 100 kPa

and P_2 = 6.0 MPa for undrained case

(Fig. 26)

This gives:

V_2 = 0.166 ml.

Therefore the volume of air for the loading in Fig. 26 will be reduced to 0.166 ml or less than 0.1% of the air free volume of the oilseeds, for the extreme assumption that all the internal air is trapped between solid tissues. It is unlikely that such a small volume of air will cause a significant deviation from the spring analogy. Lambe and Whitman (1969) have reported that soils of as low a saturation as 97% (3% air) behave like saturated soils in consolidation studies. Secondly it is unlikely that plant material will be able to trap air at such high pressures. (i.e Fig. 26 - P = 60 atmospheres - cf. a car tyre will burst when the pressure exceeds 4.0 atmospheres). It is likely therefore that any air trapped between solid tissues will be expressed into the oil where it will dissolve as already explained.

Any air present either internal or intra-kernel will dissolve in the oil and it is unlikely that air is the cause of the low pore pressures measured, in particular during undrained compression. Thus the deviation from the spring analogy used in soil consolidation studies most likely is caused by structural differences between oilseeds and other porous material where the analogy is applicable.

3.4 CONCLUSION.

It has been shown in this chapter that oil can be expressed from whole untreated cashew and rapeseed at ambient temperature and moderate pressures. Temperature and pre-crushing increase the efficiency of expression but are not as it has been emphasised in the oil expression literature the controlling parameters. Reduction of drainage area has more effect on the amount of oil expressed than temperature. The rate of expression is quite high in the initial period (first 150s) of pressing and decreases gradually until it is quite low at times in excess of 900s The shape of the curves for variation of volume of the oilseeds and volume of oil expressed are similar to settlement curves in consolidation of soils. There are intra-kernel voids when oil expression commences and these are filled with air which dissolves in the oil as the pressure increases. Part of the applied pressure is carried by the oil as fluid/pore pressure as in equation (6) of Terzaghi (1943). However, the fraction of the applied pressure carried by the oil is quite small compared to other cases of porous material as the consolidation of soils. In undrained compression for example the spring analogy does not apply the fluid pressure is only 25% of the applied pressure until above a critical applied pressure (σ_{Tc} and σ_{Tr}) when the fluid pressure becomes then equal to the applied pressure. It will be shown later (cf section 4.4.) that these samples showed a marked microstructural difference from other samples when examined under a microscope). The oil expression literature has emphasised on the need for pre-crushing and cooking of the oilseeds prior to expression to rupture the cellwalls, however, it has been shown in this chapter that substantial oil expression can occur without any of these pre-treatments.

Due to the fact that oil could be expressed from raw, un-pre-treated seeds at ambient temperature from rapeseed and cashew kernels, contrary to the expected b behaviour according to oil expression literature, it was necessary therefore, to undertake microscopic studies of the oilseeds before and after oil expression to determine any micro-structural changes brought about by oil expression.

CHAPTER 4: MICROSTRUCTURE OF RAPESEED AND CASHEW.

4.1. INTRODUCTION.

In section 2.1. the two conflicting models of the cell structure of oilseeds existing in the literature were outlined. These are the non-porous cell wall model assumed in most oil expression literature (Norris 1964) and the porous cell wall model proposed more recently by plant physiologists (Diekert and Diekert 1972,1976). In the former model the need to rupture the cell wall by mechanical and thermal action before substantial oil expression can occur is emphasised while in the latter model it is suggested that the pores on the cell wall (plasmodesmata) might be the channels through which oil flows out of the seed cell during expression.

In Chapter 3 it was shown that substantial oil can be expressed without any mechanical and/or thermal pretreatment from whole seeds. Further it was shown that oil expression commences while there are still intra-kernel voids. This would suggest that the oil has to flow out of the seed kernel and enter these intra-kernel voids before it is subsequently expressed out of them. Whether the cell walls are ruptured or not during expression, the low pore pressures reported in Chapter 3 and the fact that the individual seed kernels are only slightly deformed after expression would suggest that there is no equilibrium between the pressure of the oil in the intra-kernel voids and that within the seed kernel. In this chapter therefore it is intended to establish whether the cell walls are ruptured or not during expression and establish the mechanisms of oil flow within the seed kernel. This will be done by microscopic examination of the oil seeds before and after oil expression.

4.2 LIGHT MICROSCOPY

Thin sections (approximately 1μm) were cut by surgical blade from cashew and rapeseed kernles. The following samples were examined:

(i) untreated cashew and rapeseed.

(ii) kernels with about 70% oil expressed under constant rate of strain.

(iii) kernels heated at 120°C for 1 hour and with 90% oil expressed under constant rate of strain.

(iv) kernels with over 80% oil expressed at constant rate of loading followed by constant load.

These sections were placed in slides and stained with toluene blue for observation of the cell wall. Observation of the slides under an optical microscope revealed little difference in the cell wall structure for the four treatments (i) through (iv).
Fig. 29 (a),(b) are typical micrographs from light microscopy. It is however difficult to make definite conclusions on the cell structure and indeed mechanisms of oil expression from light microscopy. Because of this it was necessary to undertake electron microscopic investigation.

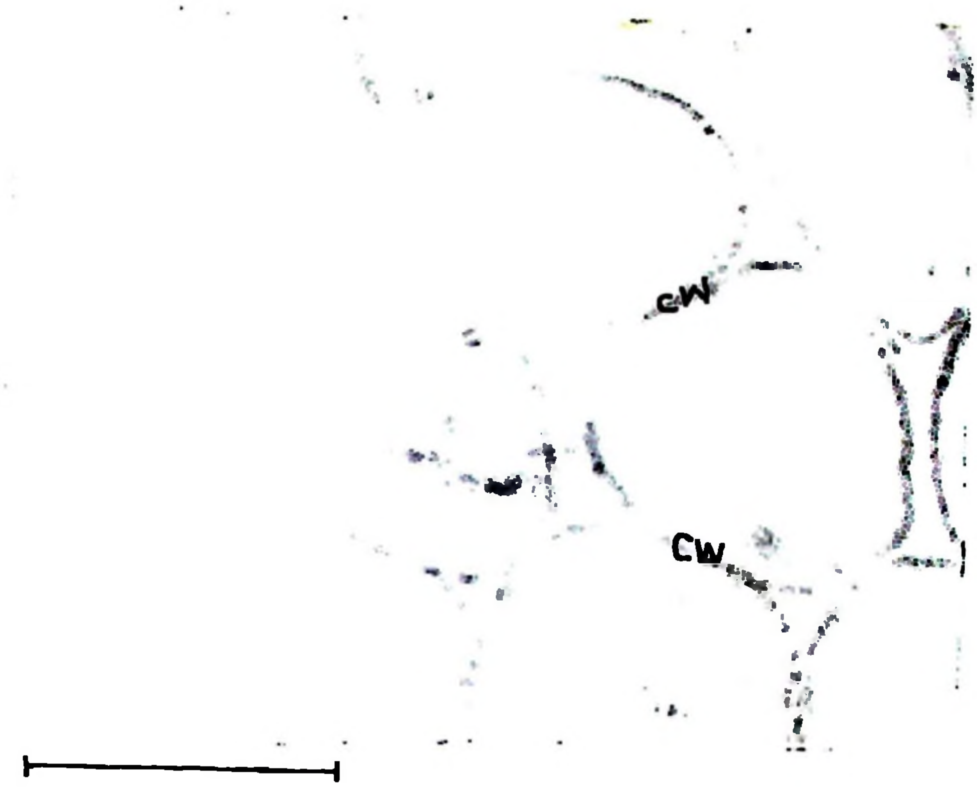


FIG. 29 (a) - LIGHT MICROSCOPY MICROGRAPH OF RAPESEED - UNTREATED.
Magnification: bar = 20µm. Staining-Toluene blue for cellwalls.

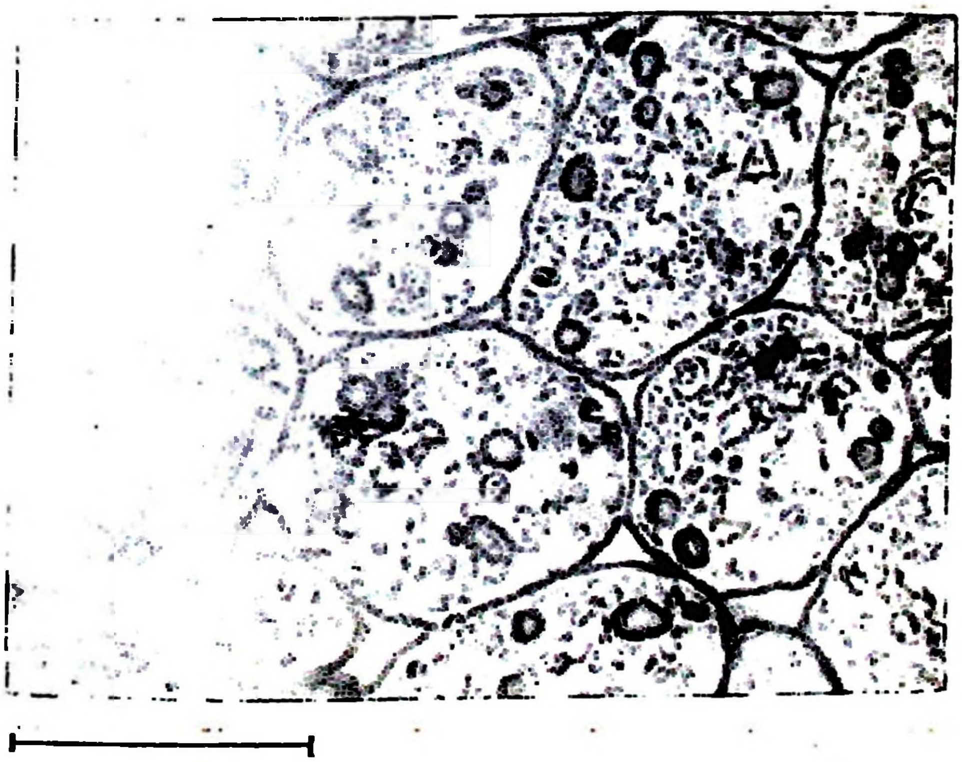


FIG. 29 (b) - LIGHT MICROSCOPY MICROGRAPHS OF RAPESEED - WITH 90% OIL EXPRESSED AFTER HEATING FOR 1 hr. at 120°C and PRESSED AT CONSTANT RATE OF STRAIN.
Magnification: bar = 20µm. Note: Cellwalls not ruptured cf(Fig 29a).

4.3. TRANSMISSION ELECTRON MICROSCOPY (TEM) OF RAPESEED AND CASHEW.

4.3.1. EXPERIMENTAL PROCEDURE

Segments (1 mm^3) were cut from the core of cashew and rapeseed kernels by a razor blade. These samples were placed immediately in a 3.0% glutaraldehyde solution in a 0.5 M phosphate buffer for 4 hours. The segments were then post fixed in a 2.0% osmium tetroxide solution in the same buffer for 2 hours. After fixation the samples were left in a vacuum of 2 Torr for an hour and then dehydrated in an acetone series and left overnight in 100% acetone at 4^oC. Embedding was carried out using an epon - araldite resin. Infiltration was carried out over a period of 2-3 days after which the capsules were then trimmed and sectioned to 70 nm thickness in a Reichert - OM3 ultratome and mounted on form - var copper coated grids. Sections were stained by a 2% uranyl acetate solution followed by a 5% lead citrate. This preparation procedure was determined by John (1978) using trial and error until the best resolution was obtained. Specimens were then observed in a Hitachi 12A Electron Microscope while other prepared in the same way but sectioned in LkB 111 Ultra-tome were observed in a Phillips 201C Electron Microscope (Stirling 1978). Overall cell structure, dimensions and frequency were determined in each case from fifteen samples each of raw rapeseed and cashew, ten samples of rapeseed and cashew each pressed with 60 - 90% oil expressed and five samples of heated and pressed cashew and rapeseed. The principles of operation and uses of a Transmission Electron Microscope are explained in detail by among others Robards (1970) and Koehler (1973).

4.3.2. RESULTS

4.3.2.1. Overall structure

The overall cell structure of both rapeseed and cashew (Fig. 30 and Fig. 31a) appeared similar to the cell structure of other oilseeds like soyabeans, cottonseed and peanuts (Diekert and Diekert (1972), (1976); Vix et al 1972). Examination of the cell walls before and after oil expression revealed little difference indicating there was no cell wall rupture during expression. (cf Fig. 30 (a) and (b) and Fig. 31 (a) and (b)). This suggests that the porous cell wall model of microstructure of oilseeds (cf section 2.1) is more likely to apply to oil expression. Additional evidence of the porous nature of the cell wall was pores on the cell wall.These pores are shown at higher magnification for the same samples in Fig. 32 a and Fig 32 b for rapeseed and cashew respectively. It was concluded therefore that these pores (plasmodesmata) were the channels through which oil expression occured.

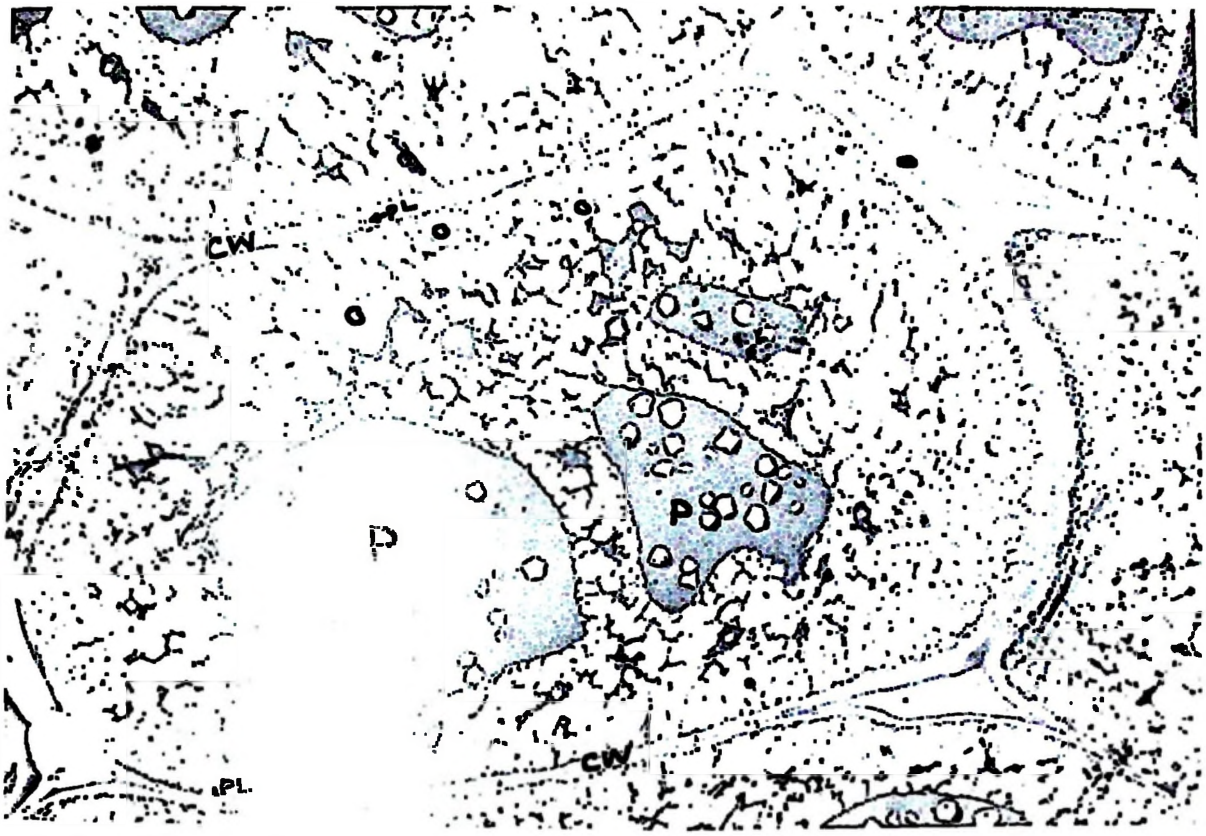


FIG. 30a MICROSTRUCTURE OF RAPESEED BEFORE OIL EXPRESSION.

O- Oil, P - Proteins, CW- cellwall
PL - Plasmodesmata (pores). 4μm.

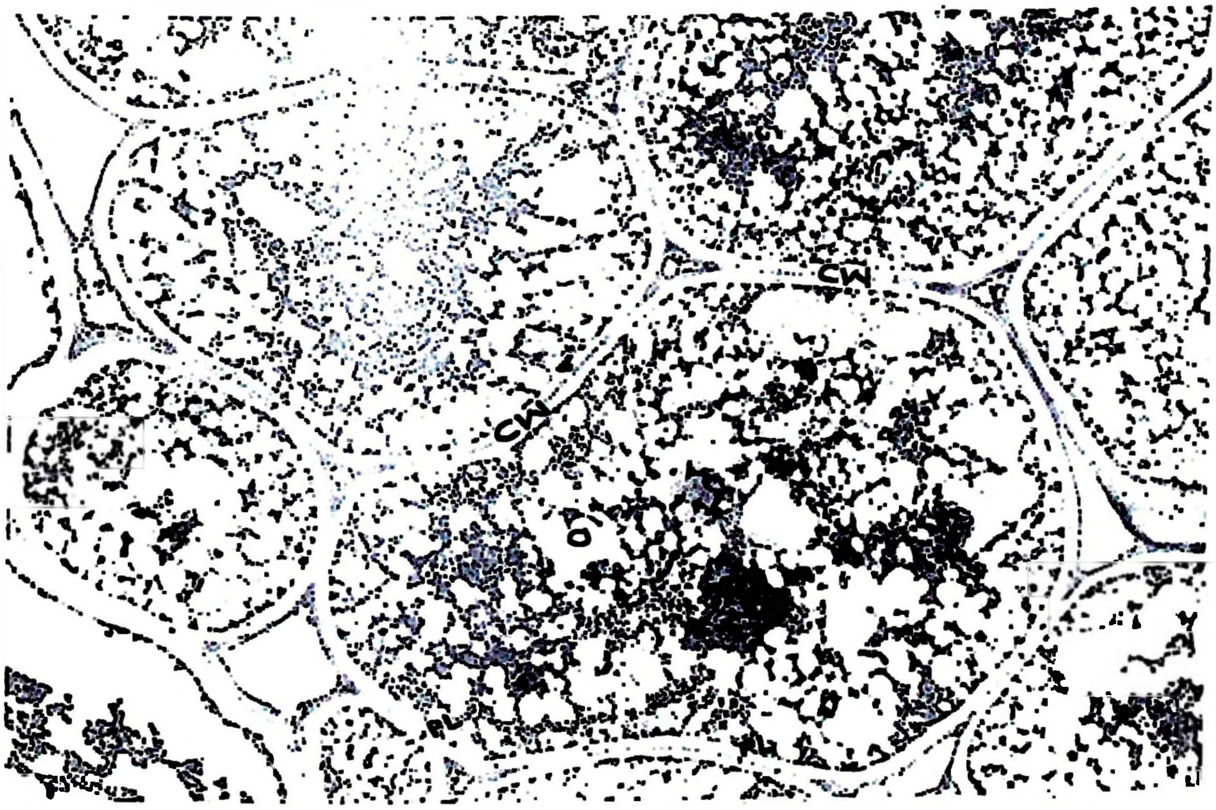


FIG. 30b MICROSTRUCTURE OF RAPESEED AFTER OIL EXPRESSION 4μm

Unruptured cellwalls CW; PL - Plasmodesmata

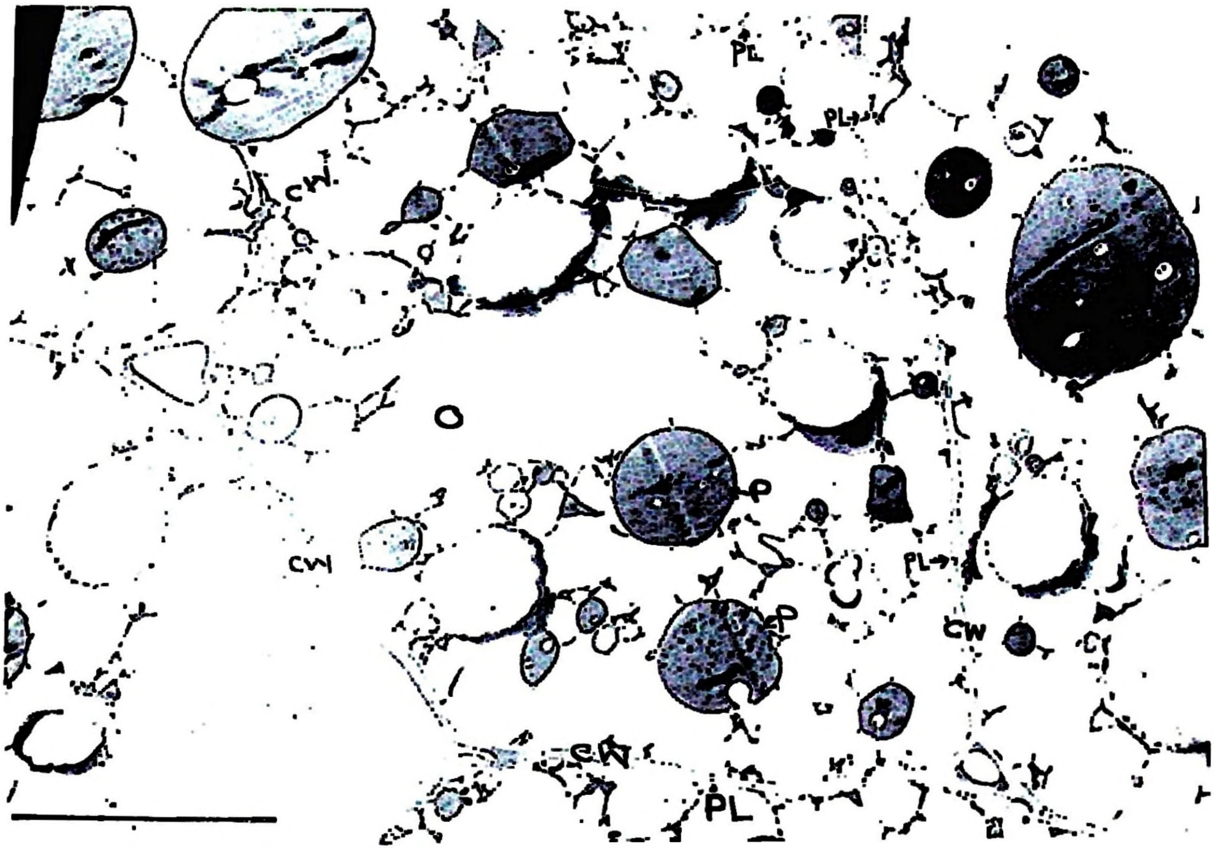


FIG. 31(a) MICROSTRUCTURE OF CASHEW: BEFORE OIL EXPRESSION.

O - Oil, PL= Plasmodesmata on cellwall (cw)

P - Proteins magnification bar = 10μm

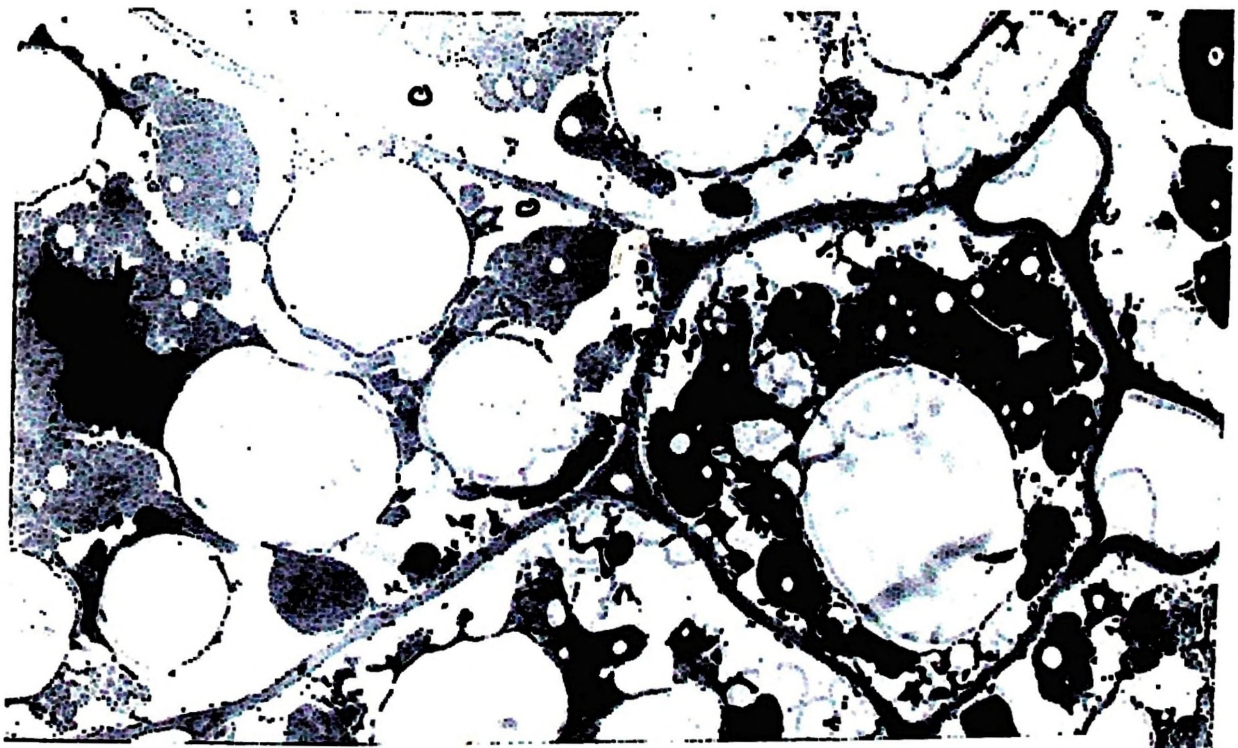


FIG. 31b: MICROSTRUCTURE OF CASHEW AFTER OIL EXPRESSION c.f Fig. 31a

Unruptured cellwalls (cw) Less oil

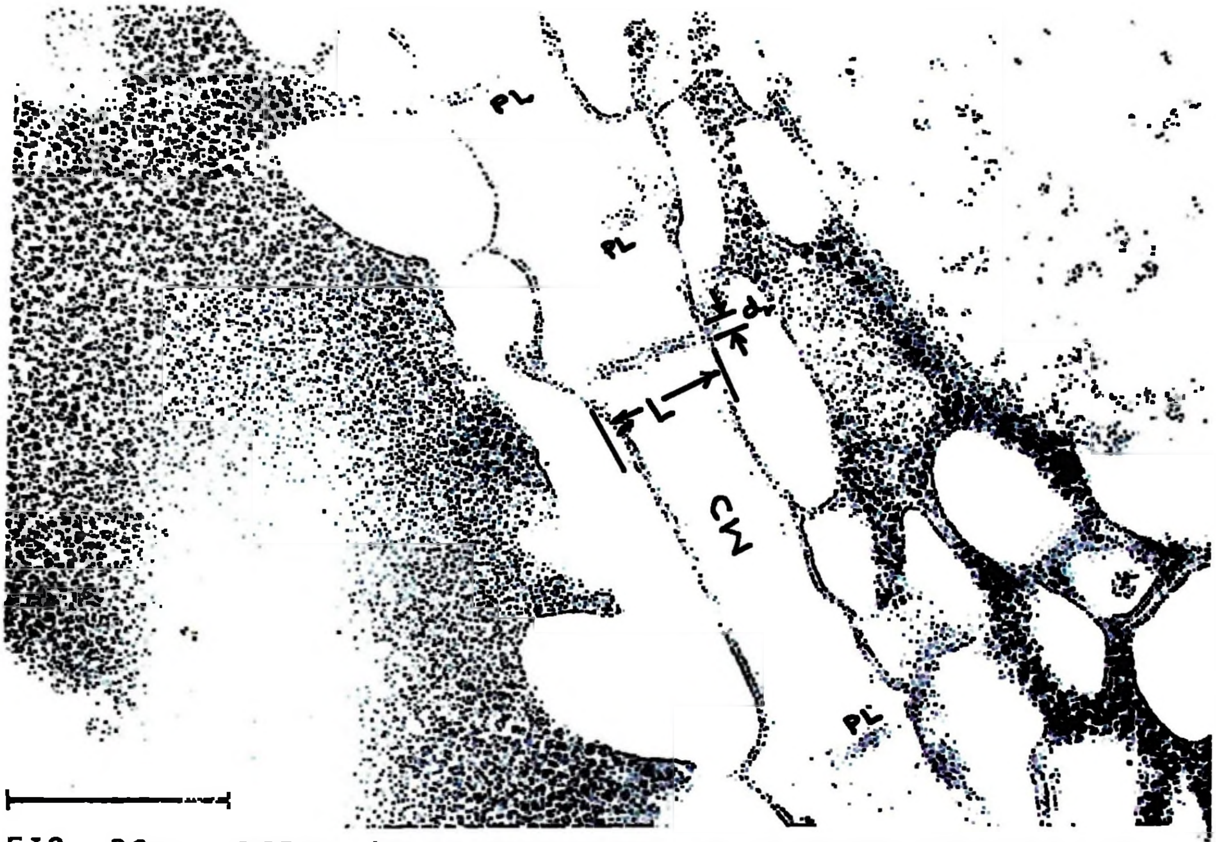


FIG. 32a: PORES (PLASMODESMATA) ON RAPESEED CELLWALLS AT HIGH.

d_r - Diameter of Pore (PL)
L = Cellwall (cw) thickness. Magnification bar = 1µm.

FIG. 32b: PORES (PLASMODESMATA) ON UNPROCESSED CASHEW CELLWALLS, AT HIGH MAGNIFICATION.

PL - Plasmodesmata, L = Cellwall (CW)thickness
Magnification: bar = 1µm. d_c = Diameter of

The only other way by which the oil could be expressed in the absence of cell wall rupture would be by diffusion through the cell wall which is unlikely to be of sufficient magnitude under typical mechanical expression conditions. It was necessary therefore to obtain dimensions of these pores (plasmodesmata) together with their frequency on the cell wall for mathematical analysis of flow of oil within the seed kernel.

4.3.2.2. Plasmodesmata diameter and length.

The diameters of the plasmodesmata (d) for both rapeseed and cashew were measured from micrographs obtained at a magnification varying from 24,000 - 48,000 (cf Fig. 32 a and b). The average diameter from 16 measurements each of cashew and rapeseed plasmodesmata gave diameters of 126.6 ± 7.0 nm and 87.1 ± 3.5 nm respectively. (Table 9). Attempts to get higher magnification (< 50000) failed due to poor resolution. In a review of plasmodesmata diameters Robards (1976) gives figures ranging from 30 nm to 500 nm. However most of the diameters measured so far are of plasmodesmata in the cell walls of roots and stems. There are no reported data on the plasmodesmata in storage (endosperm) cell walls (Robards 1978).

TABLE 9(a): PLASMODESMATA DIAMETER IN RAPESEED.

Dimensions on Micrograph (mm)	Magnification	True Demensions plasmodesmata (nm)
2.0	27000	74.1
2.5	27000	92.6
2.0	27000	74.1
2.0	27000	74.1
2.5	24000	04.2
2.0	24000	83.3
2.0	27000	74.1
2.5	27000	92.6
3.0	27000	111.1
2.0	27000	74.1
3.0	27000	111.1
2.0	27000	74.1
5.0	48000	104.2
2.0	27000	74.1
4.0	48000	83.3
2.5	27000	92.6

Average Diameter $\overline{d_1}$ = 87.1 ± 3.56 (nm)

TABLE 9(b) PLASMODESMATA DIAMETER IN CASHEW.

Dimension on Micrograph (nm)	Magnification	True dimensions plasmodesmata (nm)
5.0	36000	138.8
3.0	36000	83.3
4.0	36000	111.1
3.5	36000	97.2
7.0	36000	194.4
4.5	36000	125.0
6.0	36000	166.7
5.0	36000	138.8
4.0	3000	133.3
4.0	36000	111.1
5.0	36000	138.8
3,5	36000	97.2
12.0	100000	120.0
4.0	30000	133.3
3.5	36000	97.2
5.0	36000	138.8

Average diameter $\overline{d_c}$ = 126.6 ± 7.0

Diekert and Diekert (1972,1976) have reported the presence of plasmodesmata in the cell walls of cottonseed, peanuts, and soyabeans and suggested their possible use as oil flow channels during expression but no attempt was made by them to determine the plasmodesmata diameter and frequency. Taking rough measurement of the plasmodesmata diameter from their micrographs at low magnification, the diameter of plasmodesmata in cottonseed, soyabean, and peanuts will appear to be in the region of 5 0 - 100 nm. Observing the plasmodesmata after oil expression (Fig. 33 a and b) showed that they were still intact with the plasmallema lining disrupted.

The small size of the plasmodesmata diameter raises the question whether bulk flow can occur through such small pores. In filtration theory where the fluid flow is entirely bulk the following range of pore sizes are used to describe the different categories of filtration:(Mears, 1976).

Ultra-filtration - pore diameter 0.7 nm to 45 nm.
Particulate filtration - pore diameter greater than 45 nm flow entirely bulk.

Secondly in consolidation of soils - the average clay particles diameter range from 0.1 μm to 10 μm thus suggesting the pores in clay will be smaller than 0.2 μm. As the plasmodesmata diameters are in the

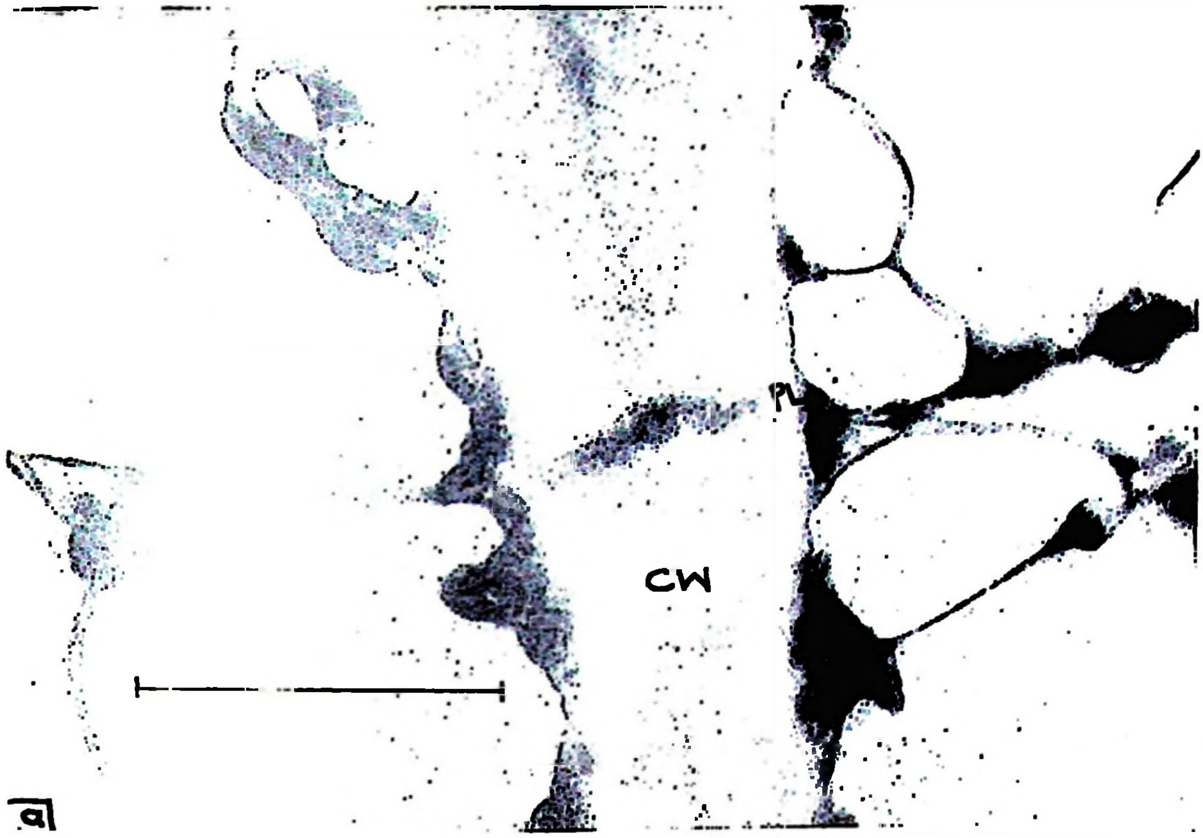


FIG. 33 (a,b) PLASMODESMATA IN (a) ABOVE - RAPESEED and (b) BELOW - CASHEW AFTER OIL EXPRESSION.
PL - Plasmodesmata CW - Cellwall.
Magnification bar = 1μm.

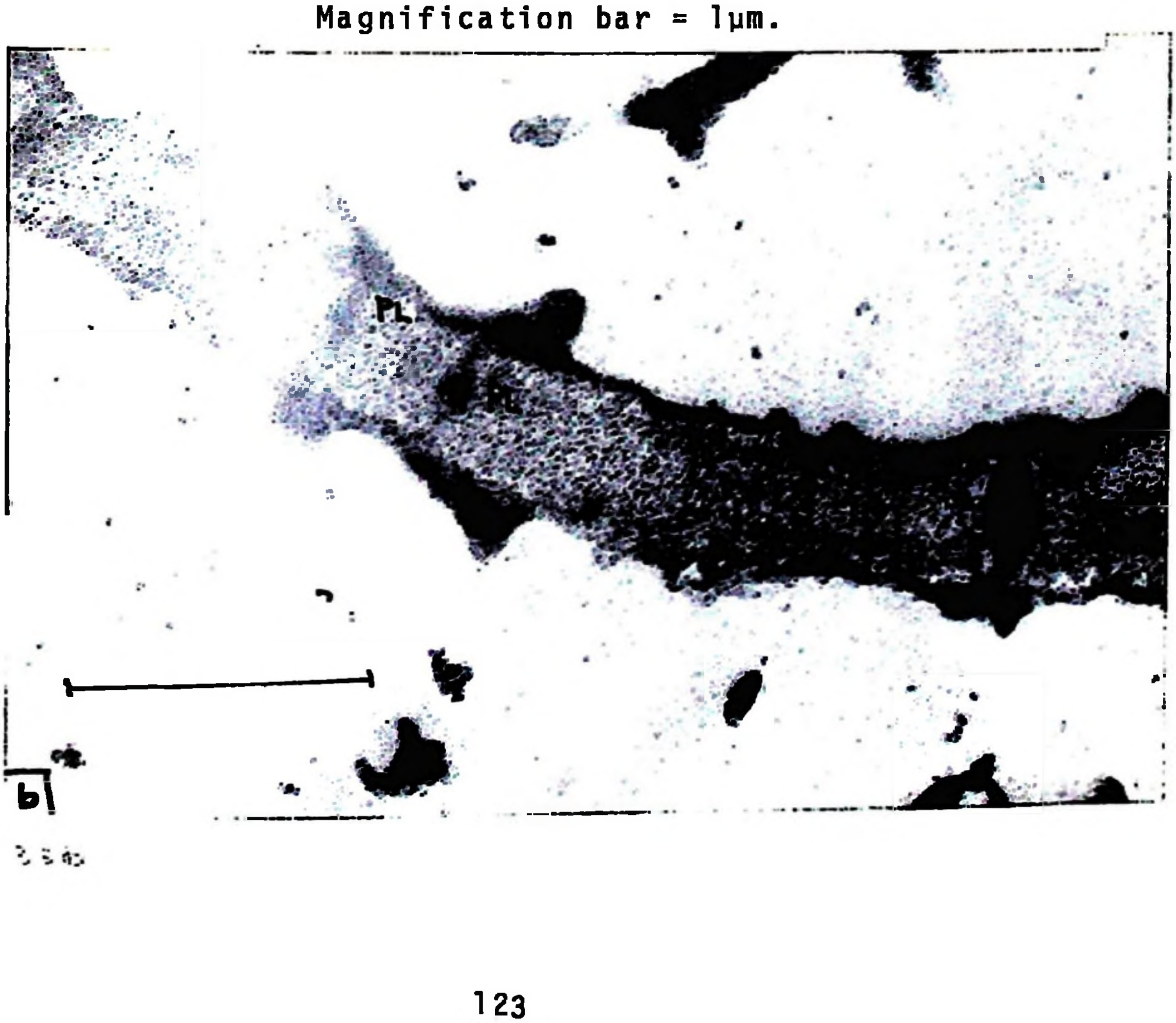


TABLE 10: CELL WALL (i.e. PLASMODESMATA) THICKNESS.

	RAPESEED			CASHEW		
	Thickness of cell wall on micrograph (mm)	Magnification	True Dimension of cell wall thickness (nm)	Thickness of cell wall on micrograph (mm) (L")	Magnification	True Dimension of cell wall thickness (nm)
1.	33.0	27000	1222.2	19.0	36000	527.7
2.	27.0	27000	1000.0	18.0	36000	500.0
3.	26.0	27000	962.0	13.0	36000	361.1
4.	15.0	24000	625.0	17.0	36000	472.2
5.	18.0	27000	666.1	16.0	36000	444.4
6.	25.0	27000	925.9	22.0	36000	611.1
7.	19.0	27000	703.7	19.0	36000	527.8
8.	29.0	27000	1074.1	21.0	36000	583.8
9.	16.0	24000	666.7	19.0	36000	527.8
10.	25.0	27000	925.9	22.0	36000	611.1
11.	21.0	27000	777.8	17.0	36000	472.2
12.	26.0	27000	962.9	19.0	36000	527.8
13.	28.0	27000	1037.0	13.5	30000	450.0
14.	34.0	27000	1259.3	62.0	100000	620.0
15.	36.0	48000	750.0	13.0	36000	361.1
16.	50.0	48000	1041.7	10.0	30000	333.3
	$\bar{L}_r$ = 912.6 (nm) ± 49.1 (nm)			$\bar{L}_c$ = 495.7 ± 22.6		

region of 100 nm this falls in the region of particulate filtration where flow is entirely bulk. The cell wall can therefore be regarded as a filter when a pressure is applied on the cell, allowing the oil to flow out through the pores and retaining the solids within the cell.

The plasmodesmata length which is equal to the cell wall thickness was measured at different points and for various cells. The average value for 16 measurements each for rapeseed and cashew was 912.6 ± 49.1 nm and 495.7 ± 22.6 nm respectively (Table10).

4.3.2.3. Plasmodesmata frequency.

Robards et al 1973 note that the estimation of plasmodesmata frequency is subject to comparatively large sampling errors. They further note that determining plasmodesmata frequency from longitudinal sections (as in Fig. 31 a,b) is less accurate than from transverse sections although longitudinal sections are inevitable in thin walled cells.

Plasmodesmata tend to appear in groups (Robards et al 1973; Burgess, 1971 Kwaitkowska and Maszewski, 1976). When cutting thin sections (<0.1 mm thick) the chances of cutting through a plasmodesmata will depend on their frequency per unit area of the cell wall surface. A large sample is therefore required for any meaningful result on the frequency in particular when the frequency of plasmodesmata is low. The frequency of plasmodesmata per unit area is determined from longitudinal sections, by counting them, and dividing the number so obtained by circumference of the cell. The figure obtained is squared to get the frequency per unit area. Micrographs were taken at low magnification (1500 - 300 where a whole cell could appear in a single micrograph) and the number of plasmodesmata in these cells were counted and circumference of the cell measured (Fig. 34 a and b). Thirty micrographs were used for cashew and twenty-eight for rapeseed. Typical micrographs and the number of plasmodesmata are shown in figure 34 a and b. Table 11 and 12 shows the plasmodesmata frequency results for cashew and rapeseed. The frequencies were0.137 ± 0.014 and 0.156 ± 0.019 plasmodesmata per μm^2 for cashew and rapeseed respectively.

There are no comparable figures in the literature for the frequency of plasmodesmata in storage cells (endosperm cells). In a review of frequencies of plasmodesmata published Robards (1976) gives figures ranging from 0.008 plasmodesmata/ μm^2 to 140 plasmodesmata μm^2(cf: plasmodesmata frequency for rapeseed and cashew of 0.156 and 0.137 plasmodesmata/ μm^2). The results obtained for plasmodesmata frequency in rapeseed and cashew would appear to be on the lower side of Robards reviewed results although he points out that he could not guarantee the statistical accuracy of the figures in the review other than those from his own publications which are less than 0.5 plasmodesmata /μm^2

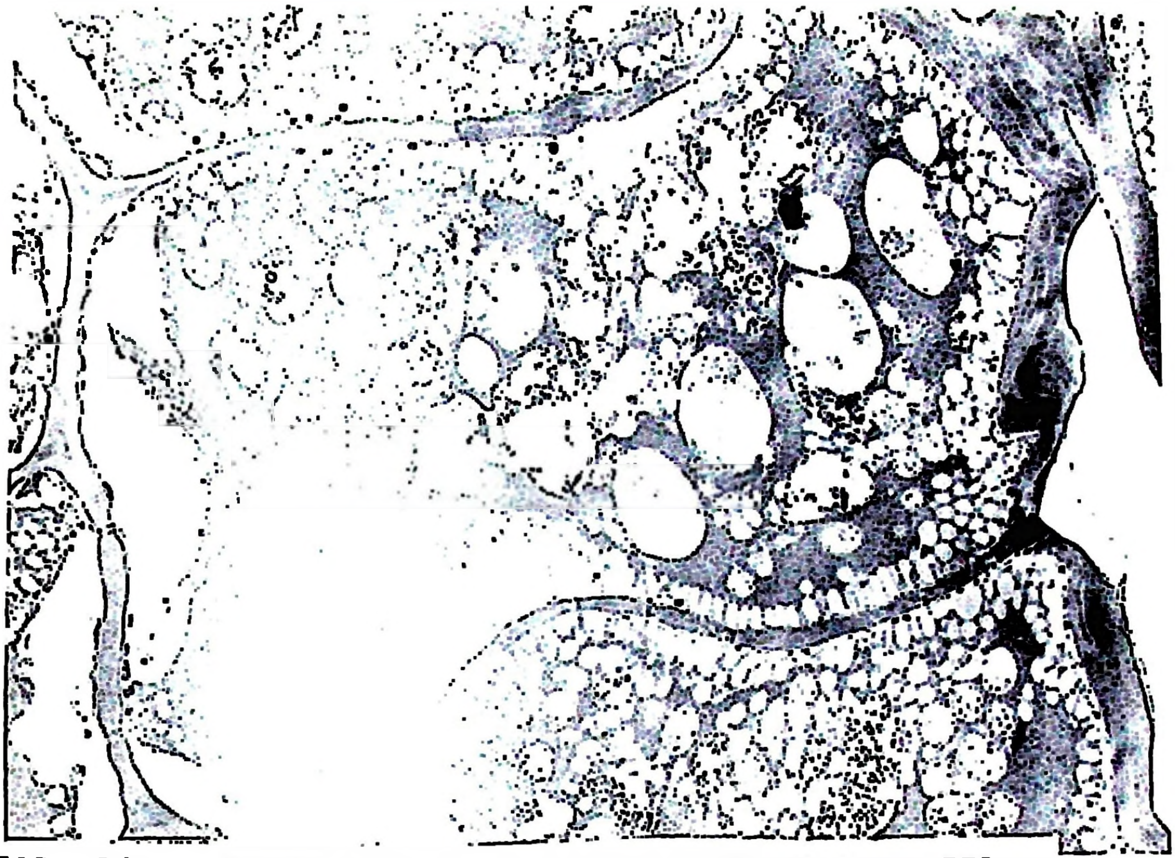


FIG. 34a FREQUENCY OF PLASMODESMATA ON RAPESEED CELLWALLS.

rapeseed no = 15, Circumference 36.7 μm

Frequency 0.409/μm = 0.167/μm²

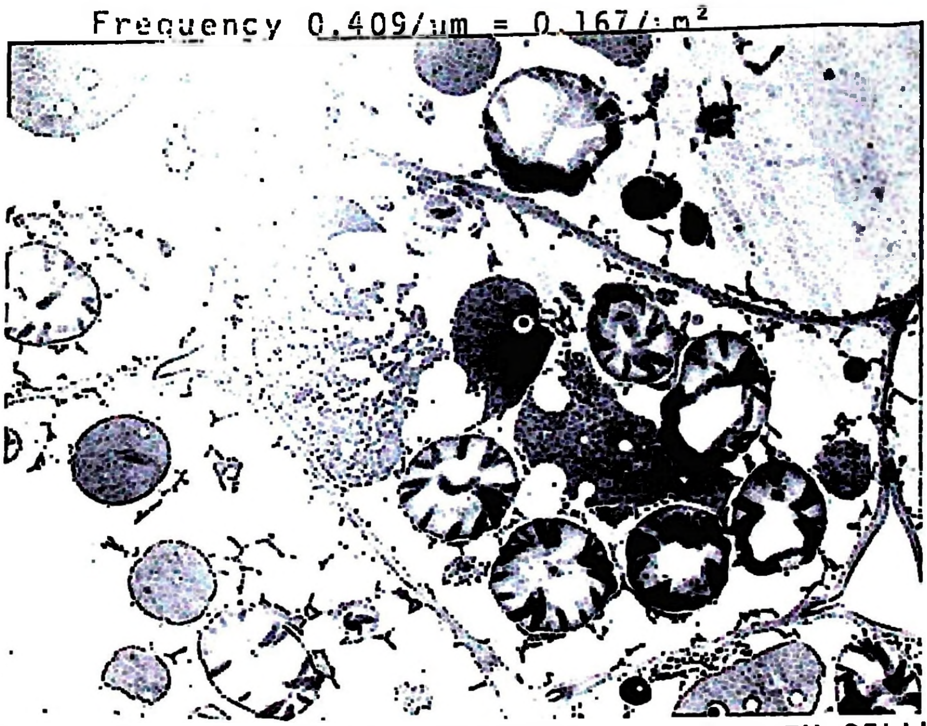


FIG. 34b FREQUENCY OF PLASMODESMATA IN CASHEW CELLWALLS

no = 12, circumference 38.2μm,

Frequency = 0.314/μm = 0.099/μm² bar =μm

TABLE 11: PLASMODESMATA FREQUENCY IN CASHEW CELLWALLS.

No.of plasmodesmata on cell circumference	Circumference of cell µm	Frequency per unit length No/µm	Frequency per unit area No/ µm²
12	38.2	0.314	0.099
19	68.5	0.277	0.077
22	63.8	0.344	0.119
18	67.7	0.266	0.071
7	16.0	0.436	0.191
9	35.7	0.252	0.064
9	20.5	0.439	0.193
26	54.6	0.476	0.227
18	70.0	0.257	0.060
19	43.6	0.437	0.191
19	40.3	0.471	0.222
11	24.2	0.455	0.207
15	45.0	0.333	0.111
30	68.1	0.440	0.194
8	14.1	0.567	0.321
17	66.3	0.256	0.066
24	52.4	0.458	0.210
15	73.3	0.204	0.042
17	70.7	0.241	0.058
8	37.3	0.214	0.046
19	67.3	0.282	0.080
10	18.6	0.538	0.289
15	64.0	0.234	0.055
7	18.5	0.378	0.143
13	26.2	0.497	0.247
18	64.3	0.380	0.078
5	12.0	0.416	0.173
14	37.7	0.371	0.138
15	65.3	0.230	0.053
14	50.7	0.276	0.076

Average frequency = 0.137 ± 0.014 (SE)/µm²

TABLE 12: PLASMODESMATA FREQUENCY IN RAPESEED CELLWALLS .

No. of plasmodesmata on cell circumference	Circumference of cell µm	Frequency per unit length No/µm²	Frequency per unit area No./µm²
7	24.2	0.290	0.084
14	50.2	0.279	0.078
23	39.0	0.590	0.348
20	52.6	0.380	0.145
34	50.8	0.670	0.448
25	41.3	0.489	0.328
27	70.3	0.384	0.148
24	66.7	0.360	0.130
20	39.5	0.506	0.256
33	52.3	0.631	0.398
21	58.0	0.362	0.131
51	121.5	0.420	0.176
44	85.1	0.517	0.267
30	107.7	0.279	0.078
19	64.6	0.294	0.087
21	43.1	0.488	0.235
22	77.4	0.284	0.081
21	42.3	0.401	0.161
15	48.7	0.308	0.095
27	80.0	0.338	0.114
10	41.3	0.242	0.059
17	28.0	0.250	0.063
8	29.3	0.273	0.074
19	61.3	0.310	0.096
10	36.8	0.272	0.074
15	36.7	0.409	0.167
12	45.3	0.265	0.070
13	49.3	0.264	0.069

Average Frequency = 0.156 ± 0.019 (SE) /µm²

4.3.2.4. The average cell diameter

The average cell diameter was obtained by measuring the circumference of the larger cells which were assumed to be the ones which were sectioned through their central axis. The average of 15 measurements each for rapeseed and cashew (Table 13) was 22.3 ± 1.77 μm and 20.5 ± 0.55 μm.respectively.

4.3.2.5. Summary of Microstructure results.

Table 14 gives a summary of the results of the microstructure of rapeseed and cashew namely plasmodesmata dimensions, frequency and cell dimensions.

TABLE 13: DIAMETERS OF CASHEW AND RAPESEED CELLS.

	CASHEW		RAPESEED	
	Circumference of cell (πD_c) (μm)	Diameter of cell ($\pi D_c/\pi$) D_c (μm)	Circumference of cell (πD_r) 9 (μm)	Diameter of cell ($\pi D_r/\pi$) D_r (μm)
1.	68.5	21.8	50.2	15.0
2.	63.8	20.3	52.6	16.7
3.	67.7	21.6	50.8	16.2
4.	54.6	17.4	51.3	16.3
5.	70.0	22.3	70.3	22.4
6.	68.1	21.7	66.7	21.2
7.	66.3	21.1	52.3	16.5
8.	52.4	16.7	58.0	18.5
9.	73.3	23.3	121.5	38.7
10.	70.7	22.5	85.1	27.1
11.	67.3	21.4	107.7	34.3
12.	64.0	20.4	64.6	20.7
13.	64.3	20.5	77.4	24.6
14.	65.3	20.8	80.0	25.5
15.	50.7	16.1	61.3	19.5

D_c = 20.5 ± 0.55 μm D_r = 22.28 ± 1.77 μm

TABLE 14: SUMMARY OF MICROSTRUCTURE RESULTS OF RAPESEED AND CASHEW.

	PARAMETER	RAPESEED	CASHEW
a)	Average Cell diameter (D ` (μm)	22.3	20.5
b)	Average Cell Surface Area (μm^2)	1562.5	1320.4
c)	Average Cell Volume (μm^3)	5807.3	4511.5
d)	Volume of oil in a one cell (μm^3)	2732.1	2058.3
e)	Average diameter of plasmodesmata (d) (μm)	0.087	0.126
f)	Plasmodesmata frequency (no/μm^2)	0.156	0.137
g)	Open area per unit area of cell surface (%)	0.093	υ.171
h)	Number of plasmodesmata on an average cell (fxb)	0.244	0.181
i)	Plasmodesmata Length L = Cell wall thickness (m)	0.913	0.496

4.4. SCANNING ELECTRON MICROSCOPY(SEM)OF CASHEW KERNELS

4.4.1 PROCEDURE

It was hoped to scan interior surfaces of cashew kernels to obtain a transverse view of plasmodesmata and internal surface profile in:

- Unprocessed seeds.
- seeds with about 80% oil expressed.
- seeds which had been compressed in undrained compression until the fluid pressure was equal to the applied pressure - (cf section 3).

Initially 4 X 4 X 5 mm segments of cashew kernels were cut and mounted on a SEM specimen holder and vacuum coated with gold particles. Owing to the cutting across cells and the resulting exposure of the oil within the seed cell, (it is not possible to coat an oily surface) resolution was poor and there was a lot of charging when the specimen was eventually observed under SEM. (Heyenga, 1978).

Freeze-fracturing and sputter coating was used and this yielded more successful results. Freeze-fractured samples were prepared by freezing the cotyledons in liquid nitrogen (-196^{o}C) for about 2 minutes then fracturing them manually. The main advantage of freeze-fracturing is that the fracture proceeds along structurally weak path within the seed kernel - in this case being the joints of the cells. (Bullivat 1973, Wolf and Baker 1973). The interior of the cell wall surface could be then observed. After freeze-fracturing the samples were mounted on the specimen holder and gold coated. Sputter coating was used and by this method a high vacuum wasn't necessary in the coater and as such preventing any rupture of cell wall by the vacuum (Roath et al 1978). The specimen were then observed under SEM at 25 KeV (SEM Type JEOL).

4.4.2 Results

Although freeze-fracturing and sputter coating enabled us to see the cell wall surface the problem of charging due to the higher temperatures in the SEM remained. To reduce this problem a thick coat had to be used an this in turn led to the obscuring of minute details like plasmodesmata. A low temperature transfer system would be required for successful use of SEM for oily specimens to be observed at high magnification (Robards and Crosby 1978). However at low magnification the cell wall profile could be observed. This is shown in Fig. 35 a - for raw cashew, Fig. 35 b for cashew in which 80% of the oil had been expressed by constant rate of loading, Fig. 35 c for cashew kernels with 80% oil expressed after heating for 1 hour at 120°C and Fig. 35 d which are from cashew kernels which had been compressed in undrained compression until $u = \sigma_t$ Fig.28 . There is no difference between Fig. 35a,

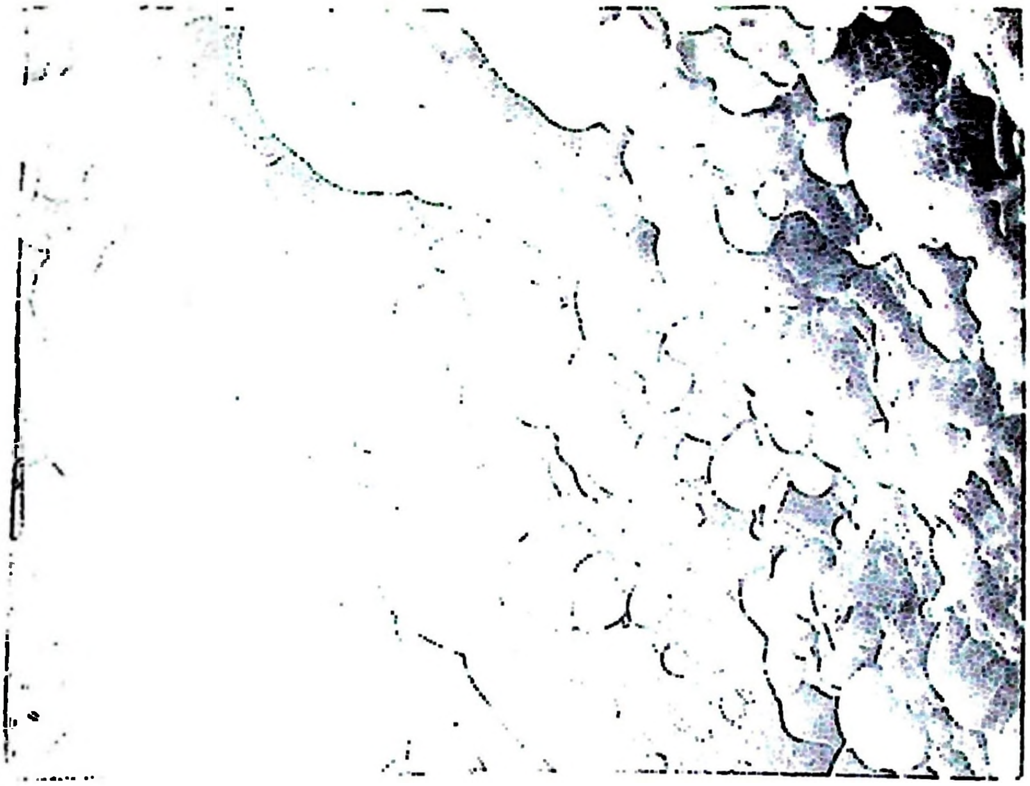
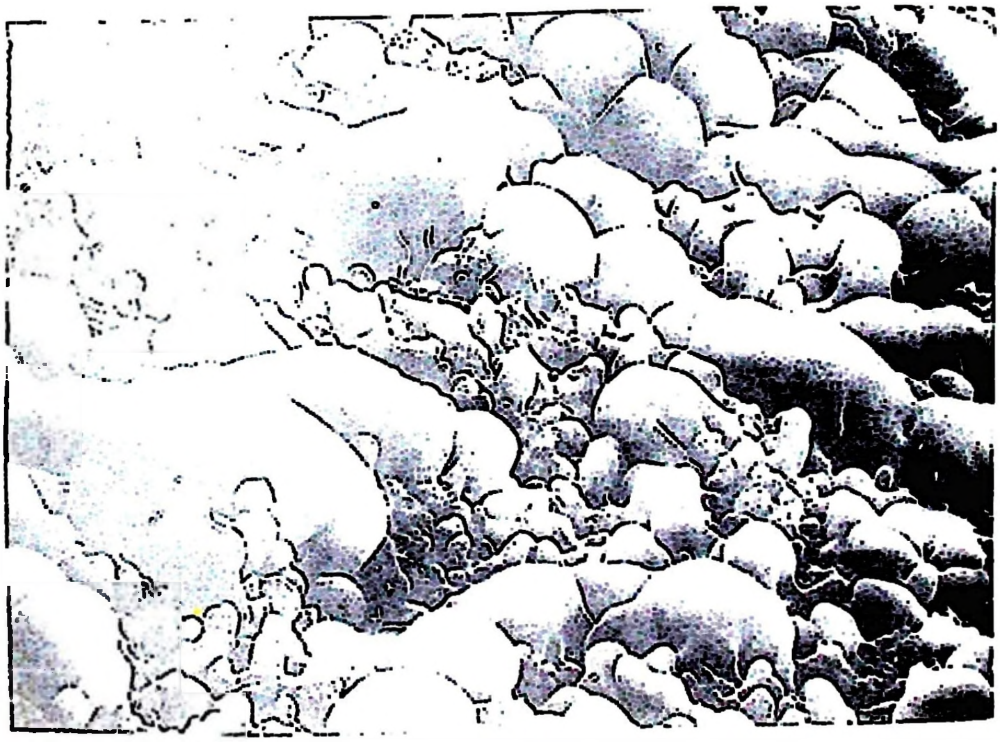


FIG. 35:(a,b) SCANNING ELECTRON MICROGRAPHS OF INTERIOR OF CASHEW KERNELS.

(a) Above - RAW CASHEW.

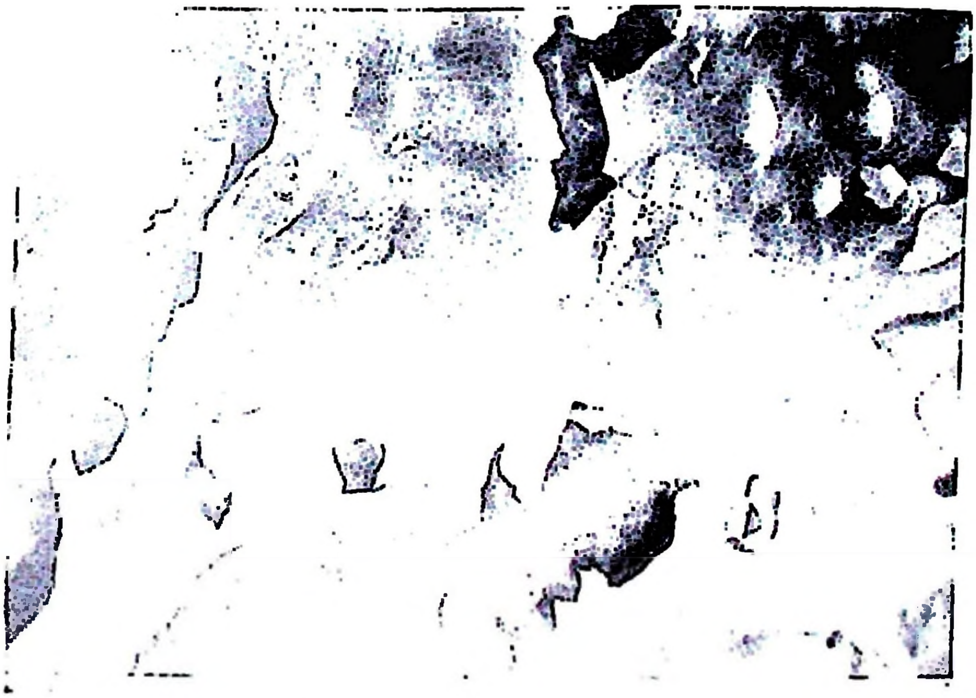
(b) BELOW - 80% OIL EXPRESSED AT CONSTANT RATE OF LOADING.



Samples: Freeze fractured and sputter coated.
Magnification X 1000

FIG. 35(c,d) SCANNING ELECTRON MICROGRAPH FOR INTERIOR OF CASHEW KERNELS.

(c) (above) Preheated at 120^{o}C and over 80% oil expressed (X 3000) cf Fig. 35a,b.



(d) Undrained Loading until $u = \sigma_T$ i.e. cell wall Failure. Note the ruptured cell-walls (cf 35a,b,c) X 1000
Both (c,d) specimen - Freeze fractured and sputter coated.

35 b and 35 c, however, the specimens from the undrained compression kernels showed a lot of holes and fractures on the cell profile (Fig. 35 c) This confirmed our earlier hypothesis that when $u = \sigma_t$. (see Chapter 3) the cell wall had been ruptured and equilibrium had been attained between the oil within the seed kernel and the oil in the intra-kernel voids and the and. the oilseeds behaved like saturated soils then.

4.5. CONCLUSION.

Microstructure studies on rapeseed and cashew show that the cellwalls are not ruptured during oil expression but they are instead porous. The pores (plasmodesmata) are of diameter 87 nm and 126 nm for rapeseed and cashew respectively. These pores are scattered all over the cellwall surface with a frequency of 0.156 and 0.137 plasmodesmata/μm^2 for rapeseed and cashew respectively giving an average porosity of the cellwalls of 0.09 and 0.171 respectively. The cellwall thickness is 0.913 μm and 0.496 μm for rapeseed and cashew respectively. Due to their small size there is a large resistance to the flow of fluids through these plasmodesmata. In addition the SEM micrograph show that cellwall rupture occurs when the seed kernels are loaded in undrained compression until $u = \sigma_T$.

From the results in Chapter 3 on expression studies and the microstructure results in Chapter 4, the oil expression process is divided into two stages:

(i) Internal flow - flow of oil within the seed kernel.

(ii) External flow - flow of oil through the intra-kernel voids.

Mathematical modelling of the expression process should therefore consider these two stages separately. In Chapter 5 internal flow will be considered further, while in Chapter 6 the external flow will be considered together with influence of internal flow on it.

CHAPTER 5: THEORETICAL ANALYSIS OF INTERNAL FLOW OF OIL

5.1 INTRODUCTION:

In Chapter 3 it was demonstrated that the Terzaghi theory of effective stress and pore pressure (equation 6) applicable to soil consolidation was to some degree applicable to oil expression, even though the fraction of the applied pressure carried by the fluid was much smaller than that in soils. Secondly during undrained compression it was demonstrated that the fluid pressure was only about 25% of the applied pressure, until the applied pressure reached a certain level when it then became equal to the applied pressure (Fig. 28) Micro-structure investigation of the oilseeds before and after oil expression showed little rupture of cell walls caused by oil expression. Instead pores (plasmodesmata) were observed in the cell wall and their dimensions and frequency on the cell wall were determined in Chapter 4 It was also shown that at the time when oil expression commenced there were intra-kernel voids which were assumed to be filled with air. Due to the high solubility of air in liquids at elevated pressure this air dissolves in the oil after oil expression has commenced.

The above points suggest that the fluid pressures measured in Chapter 3 are the pressure of the oil in the intra-kernel voids and the pressure of the oil within the seed kernel is higher than this. Thus the applied pressure is used to initiate the flow of oil through the seed kernel and into the intra-kernel voids and subsequently through the intra-kernel voids to the outside of the whole seed mass. In this chapter the flow of oil within the seed kernel will be considered. Secondly it will be shown that it is unlikely that the cell walls are ruptured during rolling and cooking before oil expression as has been suggested in the oil expression literature.

5.2 FLOW OF FLUIDS THROUGH A PLASMODESMATA

5.2.1. NATURAL FLOW THROUGH A PLASMODESMATA

Although the presence of plasmodesmata on cell walls of plant cells was known to biologists since the last century it is only recently that their function, in particular that of bulk transport through them has been quantitatively studied. Tyree's (1970) analysis of symplastic (i.e. direct) communication between plant cells is generally taken as the basis of bulk transport through plasmodesmata (Gunning, 1976). The treatment by Tyree (1970), Robards and Clarkson (1976) among others was confined to natural uptake of water and nutrients in roots and stems of plants.

The structure of plasmodesmata in roots and stems is as given in Fig. 36 (a). Tyree (1970) used a simplified model of the plasmodesmata (Fig. 36b) to mathematically model the bulk flow through a plasmodesmata. He applied the Hagen - Poiseulle equation of flow of Newtonian fluids through a pipe to flow through a plasmodesmata:

$$J_{:} = (\pi R^4 (P_1 - P_2))/8\nu L \tag{18}$$

where $J_{:}$ = Total volume of flow

R = Radius of pipe (radius of plasmodesmata)

L = Length of pipe. (cell wall thickness)

ν = viscosity of fluid flowing through pipe.

$P_1 - P_2$ = pressure drop across pipe length L.

However, in natural flow through a plasmodesmat, the plasmodesmata is like an annulus of a pipe (Fig. 36b.) and equation (18) has been suitably modified by Tyree to:

$$J = ((\pi R_1{}^4(P_1 - P_2))/(8\nu L)) \times ((1 - b^4) - (1 - b^2)^2/(\ln(1/b))) \tag{19}$$

where $b = R_2/R_1$ and R_2 and R_1 as defined in Fig. 36b.

He defined the hydraulic conductivity of a single plasmodesmata with the structure shown in Fig. 36a as:

$$L_{:} = (\pi/8\nu L) \times (R_1{}^4 - R_2{}^4 - (R_1{}^2 - R_2{}^2)/\ln(R_1/R_2)) \tag{20}$$

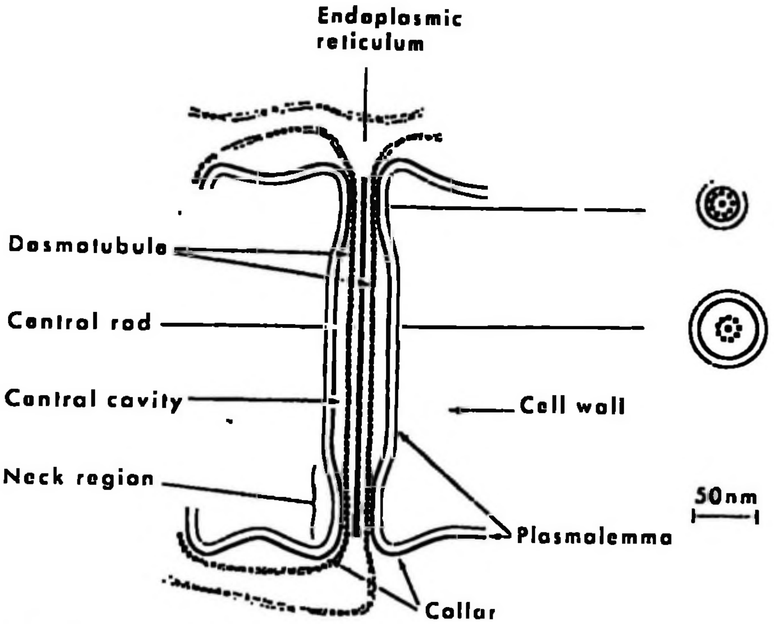
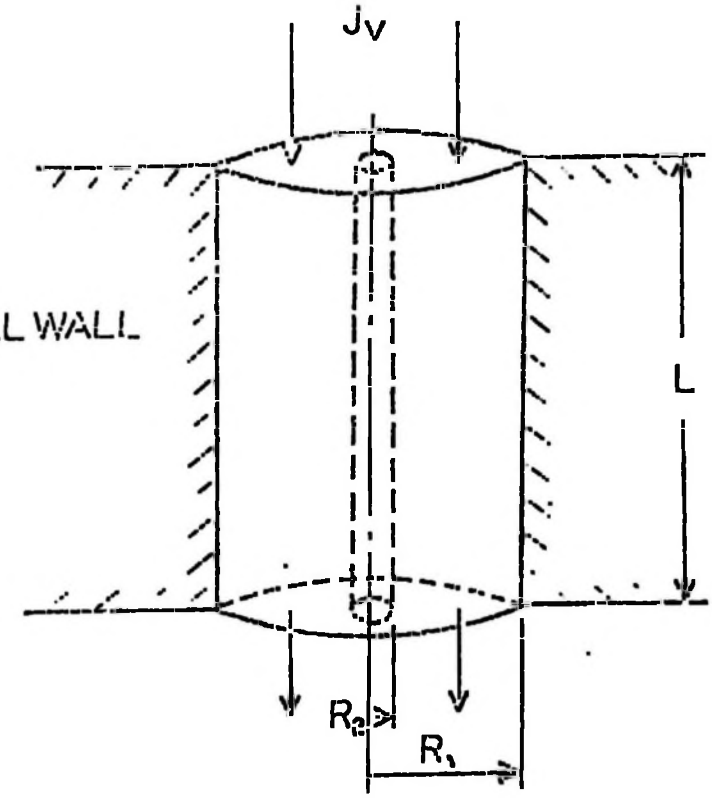


Fig. 36a The components of a simple plasmodesma. This diagram shows the various plasmodesmatal features seen in electron micrographs. It is not meant to imply any general uniformity of structure, nor specific features

From Robards (1976).

FIG. 36(b) (below) SIMPLIFIED MODEL FOR PLASMODESMATA USED BY TYREE (1970) TO MATHEMATICALLY MODEL THE FLOW THROUGH A PLASMODESMATA.



and for unit area of - cell wall, the hydraulic conductivity becomes:

$$L = NL_p \qquad (21)$$

where N = number of plasmodesmata per unit area.

Using equation (20) Tyree (1970) calculated the hydraulic conductivity for a range of plasmodesmata frequencies from 1.5 to 4 per μm^2, a range of outer radii ranging from 30 - 60nm and viscosities of 0.5 to 2.0 poise. Laminar flow was assumed, and the central rod - was assumed to be rigidly held during natural flow.

However, if the central rod is assumed to be absent then the hydraulic conductivity is given by:

$$L_p = (\pi R^4)/(8\nu L) \qquad (22)$$

where R = radius of plasmodesmata.

5.2.2 FORCED FLOW THROUGH A PLASMODESMATA.

The analysis by Tyree (1970) among others presented in section 5.2.1. was for natural flow through the plasmodesmata i.e. no externally imposed forces either inducing or assisting in the flow of liquids through the plasmodesmata. The flow of fluids in roots and stems is partly apoplastic as in animal cells (i.e.

there is a central transport vessel in stems - the phloem - where the bulk of the fluid flows) and partly symplastic (i.e. flow across the cell wall either by diffusion across the wall, or bulk flow through the plasmodesmata), whereas in storage cells such as in seeds the flow of fluids and nutrients is entirely symplastic. Carr (1976) points out that dried seeds of wheat and other cereals together with endosperm of palms have been classical objects for the demonstration of the presence of plasmodesmata in plant cell walls since the last century. However, quantitative data and studies of flow through plasmodesmata in storage cells either natural or induced by external forces is lacking in the literature (Robards, 1978). The presence of plasmodesmata in oilseeds (cottonseed, peanuts, and soyabeans) have been reported by Diekert and Diekert (1972, 1976), Vix et al (1972) among others. Hensarling et al 1970 in studies on the ultra-structural effects of oil extraction by solvents from cottonseed noted that the cell walls remained intact after extraction suggesting a porous microstructure.

The plasmodesmata structure observed in both rapeseed and cashew (Chapter 4) did not show any evidence of the presence of the central rod (the desmotubule) (Fig.32a,b) In addition Robards (1978) has suggested that it is unlikely that the plasmodesmata will retain their structure during forced flow through them and instead due to high pressures used (10 - 200 kPa) the central rod will be pushed out and mere tubes will remain on the cell wall. However,typical dimensions of the central rod range from 3 - 5 nm in diameter (Robards (1976); Tyree, (1970)) thus the value of b (the ratio of the radii) is quite small and equation (19) becomes equal approximately to equation (18). It is reasonable therefore to assume that the central rod will be pushed out and plasmallema lining disrupted during forced flow of fluids through the plasmodesmata. The plasmodesmata structure encountered during oil expression therefore would be as shown in Fig. 36b with the exclusion of the central rod. Thus using the dimensions measured for plasmodesmata (Table 14) the hydraulic conductivity of a single plasmodesmata in both rapeseed and cashew can be calculated. Using equation (22) and data from Table 14 the hydraulic conductivity for a single plasmodesmata is calculated as:

$$\text{for rapeseed } L_{pr} = 1.7 \times 10^{-23} m^5/Ns.$$

$$\text{for cashew } L_{pc} = 15.3 \times 10^{-23} m^5/Ns.$$

By equation (21) and data from Table 14 the hydraulic conductivity per unit area of cell wall is:

$$\text{for rapeseed } L'_{pr} = 2.65 \times 10^{-12} m^5/Ns \text{ (or(m/s)/Pa)}$$

$$\text{for cashew } L'_{pc} = 20.96 \times 10^{-12} m^3/Ns.$$

The above figures show that the hydraulic conductivity through cashew cell walls is much higher than in rapeseed cell walls. These values of hydraulic conductivity will be used in section 5.4 together with other expression results to model the internal flow of oil. Hydraulic conductivity ranging from 1.68×10^{-13} to 1.05×10^{-14} ((m/s)/Pa) were calculated for natural uptake of water in barley roots through plasmodesmata (Robards and Clarkson, 1976).

5.3: BEHAVIOUR OF A SINGLE CELL UNDER PRESSURE.

The oilseed cell from the microstructure data presented in Chapter 4 (Table 14) can be compared to a sphere containing oil (about 45% by volume) and solids. The walls of the cell are porous with 244 pores in rapeseed and 181 pores in cashew, and the diameter of the pores being about 0.4% of the diameter of the cell. The cell is surrounded by other cells which contain oil and solids also and the pores on the cell wall lead into these other cells. There is some trapped air in the constituents of the cell. Initially before loading the constituents are at a pressure equal to turgor pressure which provides the cell rigidity. If an external pressure is applied to the cell, initially the air will be expressed out of the tissues and will dissolve in the oil as discussed in Chapter 3. A further increase in pressure leads to the oil being expressed out of the cell through the pores on the cell wall as long as the increase in pressure is large enough to overcome the resistance of the pores to fluid flow through them, and the pressure of the oil in the cell is greater than the pressure of the oil in the surrounding cells. Thus oil expression from the cell will start when the pressure of the oil is greater than the pressure in the surrounding cells - and because of this it is necessary to consider the situation in the whole seed kernel.

5.4 FLOW OF OIL WITHIN AN OILSEED KERNEL:

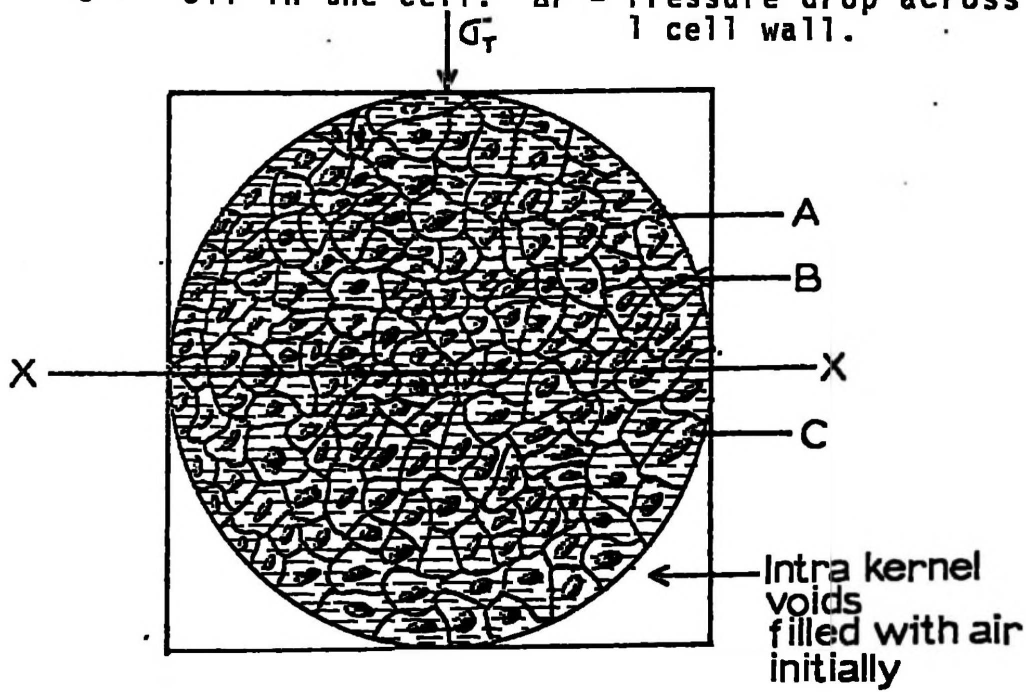
The flow of oil through a single plasmodesmata unit area of cell wall and from a single cell were considered in sections 5.2 and 5.3. In this section the flow of oil within a seed kernel will be considered. It was shown in section 5.3 that the flow of oil from a single cell will depend on the applied pressure and the pressure of the oil in the adjacent cells. Consider a single rapeseed kernel as shown in Fig. 37. When the applied pressure is increased from zero, it is assumed that before oil exprcssion commences there is a uniform increase of pressure in the oil in all the cells in the seed kernel.

The cells on the circumference of the kernel are surrounded by the intra-kernel voids on one side which before oil expression commences are filled with air at a much lower pressure than the oil in the cells, and on the other side are other cells which contain oil. If the increase in applied pressure therefore reaches the level where it can overcome the resistance of the pores on the cell walls of the cells at the circumference of the cell oil expression into the intra-kernel voids from these cells will commence. Once oil expression begins from these cells, the fluid pressure in them will decrease and this in turn will lead to oil from the second layer of cells flowing into them. This chain reaction will continue, until the cell at the centre of the kernel is reached. If uniform flow is assumed i.e. each cell gains as much oil from the

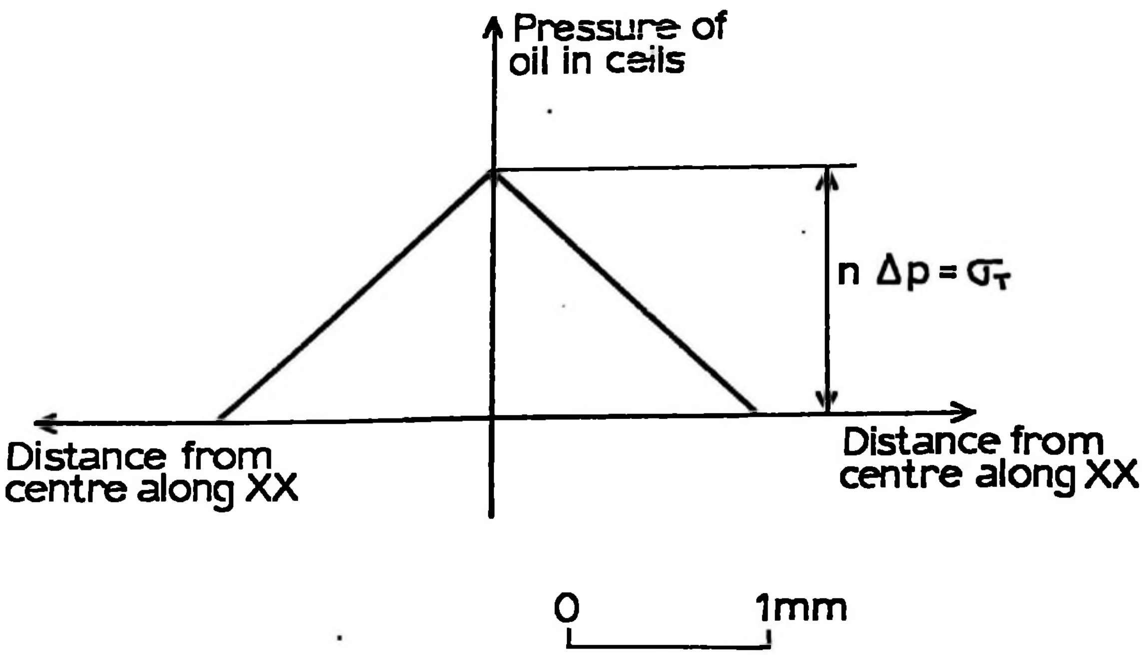
FIG. 37 PRESSURE GRADIENT IN A RAPESEED KERNEL UNDER PRESSURE.

A - Porous cellwall. B = Solids in the cell

C - Oil in the cell. ΔP = Pressure drop across 1 cell wall.



Pressure variation along XX



n = no. of cells on a radius.

inner cell as it looses to the outer cell, then a pressure gradient as shown in Fig. 37b will be set up in the seed kernel when oil expression commences.
The rate of internal flow of oil for constant temperature will depend on:

(a) The resistance of the pores on the cell wall to oil flow.
(b) The pressure of the fluid in the intra-kernel voids.
(c) The rate at which the oil is being discharged from the intra-kernel voids.
(d) The rate of application of the load σ.

At the instant when oil expression commences the pressure of the fluid in the intra-kernel voids is zero and flow from the seed kernels is entirely into these intra-kernel voids. Since uniform flow is assumed, then the flow of oil along a unit area on a radius will be constant (Fig. 38). The pressure drop and flow from each cell can be calculated. The pressure of the oil in the innermost cell (Cell 1) in Fig. 38) on a radius will be given by:

$$P_1 = n\Delta P_r \qquad (23)$$

where ΔP_r = pressure drop at each cell wall layer the oil has to cross before reaching the intra-kernel voids.

n = number of cells on a radius.

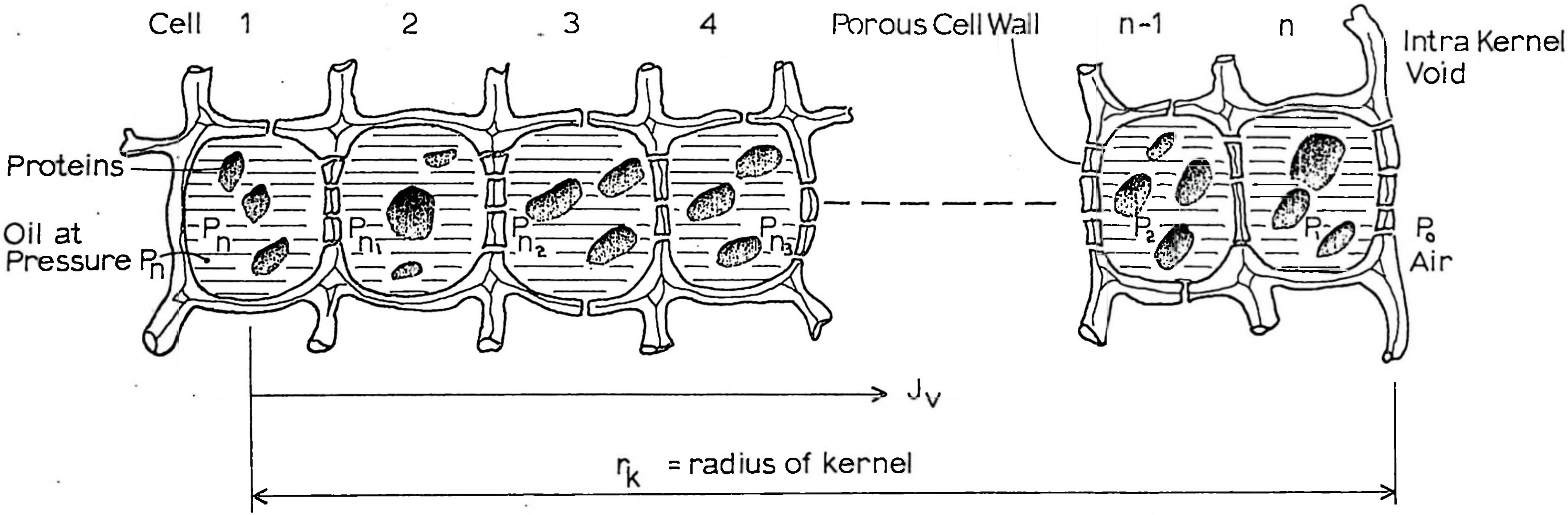


FIG. 38. FLOW OF OIL ON A RADIUS OF RAPESEED KERNEL. AT START OF EXPRESSION.

No. of cells = n = $1.25 \times 10^{-3}/22.3 \times 10^{-6}$ = 56 cells.

J = L' ΔP = Oil flow per unit area. $P_{1,2,-n}$ = Pressure in oil in cells.

P = Pressure on surrounding kernel.

The pressure of oil in cell 1 will be the highest and at the point when oil expression has just commenced will be equal to the applied pressure then-

From Table 4

P_1 = 9.05 MPa for rapeseed, and n = 56 cells.(fig. 38)

From equation (23)

$$\Delta P_r = 9.054/56 = .0.16 \text{ MPa}$$

As the hydraulic conductivity of the cell walls L'_{pr} is known and the pressure drop is known from above, the initial rate of oil expression per unit surface area seed kernel can be calculated using equation (18).

$$J_v = L'_{pr} \times \Delta P_r$$

$$= 2.65 \times 10^{-12} \ (m^3/Ns) \times 0.16 \times 10^6 \ (N/m \ )$$

$$= 0.424 \times 10^{-6} \ m/s$$

Taking an average rapeseed kernel radius of 1.25 mm, the initial total flow oil into the intrakernel voids from a single kernel is given by:

$$= J_v \times . \text{ Surface Area of a Kernel.}$$

$$= 0.424 \times 10^{-6} \ (m/s) \times 19.64 \times 10^{-6} m^2$$

$$= 8.3 \times 10^{-12} m^3/s.$$

Doing the same for cashew- (Fig. 39)

Due to it's non-spherical shape it is more difficult to determine the initial direction of flow. The shortest path is in direction 1 or 3 in Fig. 39b if each cotyledon is treated separately. If it is assumed that the initial oil expression will commence in the direction of shortest possible path, and taking an average cotyledon thickness of 6 mm, then there are 146 cells in this shortest path. Form Table 4, the pressure at which oil expression commences is 3.37 MPa and therefore:

$$\Delta P_c = \frac{3.37 \text{ X } 10^6}{146} \text{ N/m}^2 = 0.023 \text{ MPa}$$

and from section 5.2.2 the hydraulic conductivity for cashew per unit area of cell wall surface is 20.96 X 10^{-12}m^3/Ns.

The initial rate of flow from cashew is:

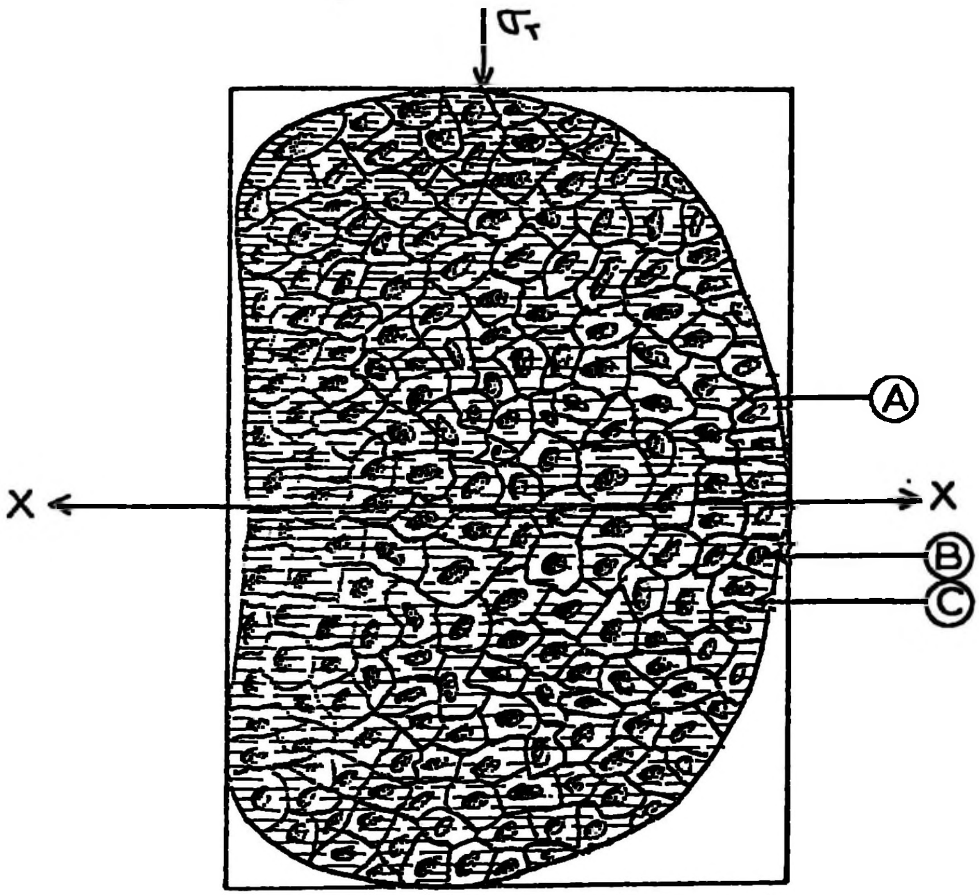
$$J_v = L'_{pc} \text{ X } \Delta P_c = 0.023 \text{ X } 20.96 \text{ X } 10^{-12} \text{ X } 10^6 \text{m/s}$$
$$= 0.48 \text{ X } 10^{-6} \text{m/s}.$$

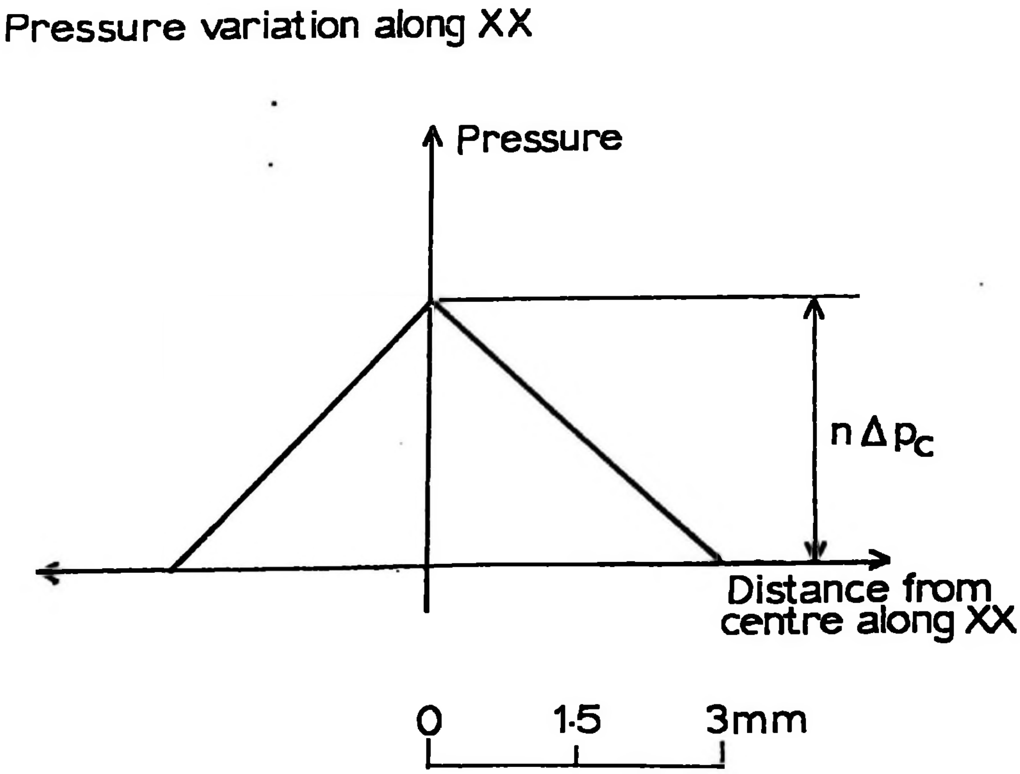
Thus even though the hydraulic conductivity per unit cell wall area for cashew is much higher than for rapeseed, the larger size of the cashew kernel reduces the effect of this microstructural advantage to oil flow in cashew compared to rapeseed such that the initial

FIG. 39. PRESSURE GRADIENT IN A CASHEW KERNEL AT COMMENCEMENT OF OIL EXPRESSION.

$$\Delta P_o = \frac{\sigma_T}{n} = \frac{3.54}{146} = 0.023 \text{ MPa}. \quad J_v = L_p \Delta P.$$

A = Porous cellwall. B = Solids. C = Oil.





rate of flow from cashew is only marginally greater than in rapeseed. This will explain partly why the amount of oil expressed from the two oilseeds was almost equal in all the tests in Chapter 3 despite the fact that cashew kernels are much larger than rapeseed kernels. The higher hydraulic conductivity of cashew cell walls also explains why oil expression in cashew kernels commenced at a lower load(3.37 MPa) than in rapeseed (9.05 MPa) (Table 4).

The oil being expressed out of the seed kernel will flow into the intra-kernel voids and it's continuous expre-ssion from within the seed kernels will be greatly influenced by the rate at which the oil is being removed from these intra-kernel voids, and it's pressure while there. Factors influencing the flow of oil from the intra-kernel voids will also influence the internal flow. These will be discussed after a theoretical analysis of the intra-kernel flow of oil.

5.5. EFFECT OF PRE-TREATMENT ON INTERNAL FLOW.

5.5.1 TEMPERATURE.

Heating the oilseeds prior to oil expression will reduce the viscosity of the oil thus increasing the hydraulic conductivity of the cell walls in direct proportion as indicated in equation (18). For example the viscosity of rapeseed oil at $20^{o}C$ and $100^{o}C$ is 0.84 and 0.094 poise (Swern 1964) respectively.

Thus the hydraulic conductivity will be increased by a factor of 8.94. The suggestions by Norris (1964), Ward (1976) among others that the heating of the seeds ruptures the cell wall seems unlikely in view of the porous structure of the cellwalls shown in Chapter 4.

5.5.2 REDUCTION OF SEEDSIZE.

It has already been shown in section 5.4 that despite the much higher hydraulic conductivity of the cell walls of cashew kernels compared to rapeseed the large size of the cashew kernels reduced this effect such that the initial rate of flow out of the kernels was only marginally higher in cashew compared to rapeseed. The effect of reducing the seed size prior to expression is to reduce the number of cell walls which the oil has to cross before reaching the intra-kernel voids, as the greatest resistance to oil flow occurs within the kernels. However, as will beshown in the next chapter although more oil will be expressed from within the seed kernels into the intra-kernel voids, such a reduction of the seed size will affect the flow from the intra-kernel voids, and as such if the seeds are ground to a fine powder it does not necessarily mean more oil will be expressed from the whole oilseed cake. Secondly if the seed particles are too small, the rigidity of the seed kernel is affected and extrusion of solids with the oil will occur (Ward 1976).

5.5.3. ROLLING OF THE OILSEEDS.

Woolrich and Carpenter (1935) observed little cell wall rupture in rolled cottonseed flakes when they examined them under a microscope. Norris (1964) agrees that it is unlikely that there is substantial cellwall rupture in cottonseed rolled to very thin flakes. In all the cases in expression literature the cell wall model used was a non-porous one as described in section 2.1. The presence of plasmodesmata in cottonseed, soyabeans, and peanuts has been shown by Diekert and Diekert (1972), (1976). In Chapter 4 we showed the presence of plasmodesmata in both rapeseed and cashew. The low speeds used in rollers (8 - 14 rpm equivalent to 0.004 - 0.007 m/s) (Norris 1964) and the porous nature of the cell wall, make it unlikely that cell wall rupture will occur when the seeds are passed through rollers. In studies on maceration properties of alfalfa Koegel et al (1973) concluded that rolling the alfalfa did not produce substantial cell wall rupture, and that extrusion of the alfalfa through orifices produced substantial rupturing of the cell wall.

5.6. CONCLUSION.

The internal flow of oil has been analysed with reference to the microstructure of rapeseed and cashew. The hydraulic conductivities of the cell walls of cashew and rapeseed have been calculated. The results show that despite the higher hydraulic conductivity of cashew cell walls, the larger size of the cashew kernels has reduced this advantage to the extent that the initial oil expression from a cashew kernel is only marginally higher than in rapeseed.

There is a pressure gradient within the seed kernel. The rate at which the internal expression proceeds is influenced by the rate of oil expression from the intra-kernel voids. Hence factors affecting the intra-kernel flow of oil will subsequently affect the internal flow. It is necessary therefore to consider the intra-kernel oil expression in conjunction with the internal flow.

CHAPTER 6: DEVELOPMENT OF A GENERAL OIL EXPRESSION EQUATION.

6.1. INTRODUCTION.

In Chapters 3 and 5 it was shown that we are dealing with a compressible porous skeleton due to expression of oil from within the seed kernels. Accordingly the applied pressure is divided into two parts - the kernel pressure used to effect the flow of oil within the seed kernels and the pore pressure used to drive the oil through the intra-kernel voids. In Chapter 5 it was shown that the flow of oil through the porous cellwalls followed the Hagen - Poiseulle equation. The flow through the intra-kernel voids is essentially a flow through porous medium and can be solved mathematically by use of Darcy's law. The compressibility of the seed kernels introduces complexities which are not found in soil consolidation where the soil grains are assumed incompressible.

Thus one has a twofold problem - the seed kernels are undergoing finite deformation (due to oil flowing out into the intra-kernel voids) and coupled with this the fluid is being displaced from the intra-kernel voids. According to Scheidegger (1961) what is required for practical study of the flow of fluids in compressible medium is a set of equations of motion for the fluid wherein due allowance is made for the concurrent deformation of the porous medium containing the fluid. It is necessary, therefore, to develop equations which will consider the flow through the intra-kernel voids and at the same time take into consideration the concurrent flow of oil from within the seed kernels into the intra-kernel voids.

6.2. DEVELOPMENT OF A GENERAL EQUATION FOR OIL EXPRESSION.

6.2.1 ASSUMPTIONS.

(a) It is assumed that a modified form of Terzaghi's equation of satisfactory model the flow of oil in a compressible oilseed cake. The modified Terzaghi equation maybe written as:

$$\sigma_t = \sigma_i + u \qquad (24)$$

where σ_t = the total applied pressure.

σ_i = fraction of the applied pressure carried by the seed kernels and which is used to express the oil from within the seed kernels. The seed kernel is a two phase (liquid - solid) medium in contrast to Terzaghi's model in which σ_e is applied to the solid incompressible soil particles.

u = fraction of the applied pressure carried by the oil in the intra-kernel voids and which is used to express it through the intra-kernel voids.

Thus this equation is applied to both internal and external flow of the oil. This assumption has been verified experimentally in Chapter 3 with q_l>>u.

(b) It is assumed further that any air present in the oilseed cake (both internal and external) has dissolved in the oil as discussed in section 3.3.6. and the oilseed cake is essentially a two phase liquid/solid sample.

(c) Darcy's law is assumed to be applicable to the flow of oil through the intra-kernel voids.

(d) It is assumed that the part of the applied pressure carried by the seed kernels σ_i is used to express the oil from within the seed kernels as discussed in Chapter 5. Thus the flow of oil from within the seed kernel can be modelled on an equation-similar to the Hagen Poiseulle equation i.e.

$$V = f(L_p', n, A_k) \times \sigma_i$$

where V = Volume flow into the intra-kernel voids per unit time.

$f(L_p', n, A_k)$ = a constant which is a function of:

L_p' = the hydraulic conductivity of the cellwalls.

n = An average number of cellwalls the oil has to cross per unit time before reaching the intra-kernel voids.

A_k = the surface area of the seed kernels in contact with intra-kernel voids through which oil flows into them.

σ_i = part of the applied pressure carried by the seed kernels.

It is assumed further that although A_k decreases with compaction of the seed kernels, an average value can be computed which will be taken as a constant for any expression test.

(e) The compressibility of the seed kernels is assumed to be solely due to oil expression from the kernel i.e. the oil and solid tissues which make up the seed kernels are incompressible.

(f) If a small element is considered size dx X dy X dz it is assumed that the element is large enough compared to the size of the intra-kernel voids that it may be treated as homogenous and small enough compared to the size of the whole seed cake that it may be considered infinitesmal in mathematical treatment.

(g) Due to small masses involved, gravity effects are ignored.

(h) It is assumed further that the value of k, the Darcy's coefficient of permeability of the intra-kernel voids is for the whole cylinder area and not only for the area of the intra-kernel voids.

6.2.2. THEORY.

Consider a small element within the oilseed cake with sides dx, dy, dz (z being the vertical direction) under pressure σ_T (which maybe increasing with time or constant). The pressure of the oil in the intra-kernel voids increases vertically upwards as the flow is vertically downwards. Thus, if the pressure of the oil in the intra-kernel voids at the bottom horizontal face is $(\partial u/\partial z)$, then that at the top horizontal face is $(\partial u/\partial z + (\partial^2 u/\partial z^2)\, dz)$. By Darcy's law flow into the top horizontal face in time ∂t is given by $(\partial q_{in}/\partial t)$.

$$(\partial q_{in}/\partial t) = (k/\rho g)(\partial u/\partial z + (\partial^2 u/\partial z^2)dz^2)dxdy$$

dxdy = Area of upper face (m^2)

ρg = specific gravity of the oil (N/m^3)

k = Darcy's Coefficient of permeability (assumed constant) (m/s)

$\partial u/\partial z + (\partial^2 u/\partial z^2)dz$ = pressure of fluid in the intra-kernel voids at the upper face.

Similarly flow out of the bottom horizontal face:

$(\partial q_{out}/\partial t)$

$$\partial q_{out}/\partial t = (k/\rho g)(\partial u/\partial z)\ (dxdy)\ (m^3/s)$$

where $\frac{\partial u}{\partial z}$ = fluid pressure at the bottom face.

Therefore, the rate of change in volume of the element in time ∂t, is given by:

$$\frac{\partial V_d}{\partial t} = \frac{\partial q_{out}}{\partial t} - \frac{\partial q_{in}}{\partial t} = \frac{k}{\rho g}\left(\frac{\partial^2 u}{\partial z^2}\right)(dxdydz) \qquad (25)$$

To get another equation for the change in volume it is necessary to consider the compressibility of the seed kernels. In Chapter 5 it was shown that due to the porous nature of the cellwalls, the flow of oil within the seed kernels followed the Hagen - Poiseulle equation. Thus, if the seed kernels are subjected to a pressure equal to σ_i (equation 24) their change in volume can be given by an equation of the form;

$$V_h/V_i = S\ \sigma_i \qquad (26)$$

where V_h = change in volume of the seeds kernels due to oil flowing into the intra-kernel voids.

where V_i = Original volume (a constant)

σ_i = part of the applied pressure carried by the seed kernels - equation (24).

S = a parameter which represents the flow out of the seed kernels in unit time per unit increase of pressure σ_i and from unit volume of the seed kernels

The rate of change in volume of the kernels is given by partially differentiating equation (26) with respect to time:

$$(1/V_i)\ (\partial V_h/\partial t) = \sigma_i\ (\partial S/\partial t) + S\ (\partial \sigma_i/\partial t) \qquad (27)$$

We now quantify the paramater S.

In assumption (d) (section 6.21) the parameter s was given as a function of: $S = f(L_p', n, A_k)$

From the Hagen - Poiseulle equation (Equation Chapter 5) the hydraulic conductivity of the cellwalls was defined as: L_p' as the flow in metre per sec per unit area of cellwall and unit increase of pressure difference across the cellwall (Δp) with units (m/s)/Pa .
In unit time the flow across 1 cellwall unit area per unit increase of applied pressure is given by L_p''

$$L_p'' = L_p' \times 1 \ \mathrm{m/Pa} . = L_p' \ \mathrm{m/Pa} .$$

If the oil crosses an average of n cellwalls at rate L_p'' per unit time before reaching the intra-kernel voids and the average area of the seed kernels in contact with the intra-kernel voids through which oil flows into thim is A_k which per unit volume of element is A_k / V_i then the parameter S is given by the expression:

$$S = L_p'' \times n \times 1 \times \frac{A_k}{V_i} \left(\frac{m}{Pa} \times \frac{1}{s} \times s \times \frac{m^2}{m^3} \right)$$

$$S = \frac{L_p'' \times n \times A_k}{V_i} (1/Pa) \qquad (28)$$

Which is the specific flow of oil out of the seed kernels in unit time, per unit volume and per unit increase of the applied pressure i.e. the specific compressibility of the seed kernels. Of the parameters involved in equation (28), L_p'', n, and V_i can be taken as constants with time in any expression test. The kernel surface area in contact with the intra-kernel voids, A_k, will vary as expression progresses and the seeds are compacted -the intra-kernel voids are reduced and hence A_k will decrease. The variation of A_k with time is difficult to determine and it will vary with rate of loading, and drainage area. It is possible, however, to calculate an average value of A_k which will be assumed to be constant throughout a particular test (assumption (d)). This,therefore,means that for any test S becomes a constant and equation 27 reduces to (as $\partial S/\partial t = 0$):

$$(1/V_i)(\partial V_h/\partial t) = S(\partial \sigma_i/\partial t.) \qquad (29)$$

But $\sigma = \sigma - u$ (equation 24)

$$\therefore \partial \sigma_i/\partial t = \partial \sigma_T/\partial t - \partial u/\partial t$$

and equation (29) becomes with initial volume V = dxdydz;

$$\partial V_h/\partial t = S(\partial \sigma_T/\partial t - \partial u/\partial t)dxdydz \qquad (30)$$

This oil flowing out of the seed kernels will displace oil - already in the intra-kernel voids which will have to flow out of them by Darcy's law.

$$\therefore \partial V_h/\partial t = \text{Change in volume of the element.}$$

and from equation (25)

$$\partial V_h/\partial t = \partial V_d/\partial t \qquad (31)$$

and hence:

$$-(k/\rho g)\ (\partial^2 u/\partial z\ )dxdydz = S(\partial\sigma_T/\partial t - \partial u/\partial t)\ dxdydz.$$

$$\therefore\ M(\partial^2 u/\partial z^2) = (\partial u/\partial t) - (\partial\sigma_T/\partial t) \qquad (32)$$

$M = (k/S\rho g)$ and a constant for a particular loading history, drainage area and time. (m^2/s).

In deriving equation (32) M has been assumed a constant, throughout a test. This in reality is an approximation as when the seed kernels are compressed both the surface area in contact with intra-kernel voids A_k and the coefficient of permeability k of the intra-kernel voids decrease. The coefficient of permeability k for soils is taken as a constant during consolidation studies even though it varies as consolidation proceeds. However, solutions with M as a constant fit reasonably well with the experimental results making this approximation reasonable. It is necessary therefore, to solve equation (32) for the two cases used in the experimental procedure in Chapter 3, i.e. for the case when the load is increasing linearly ($\partial\sigma_T/\partial t = R$ Pa/s) and when the load is constant ($\partial\sigma_T/\partial t = 0$). The two equations to be solved are therefore:

$$M\partial^2 u/\partial z^2 = \partial u/\partial t - R \qquad (33)$$

and

$$M\partial^2u/\partial z^2 = \partial u/\partial t \tag{34}$$

This will give a solution in the form $u = f(\sigma_T, R, M, z, t)$ and the rate of oil expression can then be calculated by use of Darcy's law.

6.2.3. SOLUTION TO OIL EXPRESSION EQUATIONS (33) and (34).

Equation (34) is similar to heat flow equation in a homogenous isotropic body and other diffusion phenomena and has been solved for soil consolidation (Taylor 1966) for various initial and boundary conditions. An equation similar to equation (33) has been solved by use of Duhamel's Theorem (Wylie 1966; Myers, 1971) for heat transfer problems in internal combustion engine walls (heat input into the wall varies with time cf. $\partial\sigma_T/\partial t$ - energy input into the oilseeds varies with time). Schiffman, (1958) and Aboshi *et al*, (1970) have applied these solutions to the problem of consolidation of soil under a time dependent loading.

In the experimental procedure in Chapter 3 a linearly varying load followed by a constant load was used.

Thus for equation (33):-

$$M(\partial^2 u/\partial z) = (\partial u/\partial t) - R$$

the initial conditions are:-

$$u = 0, \; t = 0(s);$$

and boundary conditions;

$(\partial u/\partial z) = 0$ at $z = H$ - no drainage at top.

and $u = 0$ at $z = 0$

H in the above case is the length of the longest initial drainage path (Hough; 1957); Scott (1974).

The solution for equation 33 is given by the series:-

$$u(z,t) = \frac{16H^2R}{\pi^3 M}\left[\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^3}\left\{1-\exp\left(\frac{-(2n+1)^2 \pi^2 Mt}{4H^2}\right)\right\} \times \left\{\sin\left(\frac{(2n+1)\pi z}{H}\right)\right\}\right)\right] \quad (35)$$

Equation (35) gives the solution for u, the intra-kernel fluid pressure at any time t and height z of the oilseed cake. By Darcy's law it is known that the rate of flow at any instant of time is given by $q = \partial q/\partial t = (k/\rho g)(\partial u/\partial z)$

$$\therefore \quad \frac{\partial u}{\partial z} = \frac{16HR}{\pi^2 M}\left[\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^2}\left\{1-\exp\left(\frac{-(2n+1)^2\pi^2 Mt}{4H^2}\right)\right\} \times \left\{\cos\left(\frac{(2n+1)\pi z}{H}\right)\right\}\right)\right] \quad (36)$$

The total flow from time $t = 0$ to $t = t_r$ is given by the integral (per unit area)

$$Q_t' = \int_0^t \frac{\partial q}{\partial t}\, dt \qquad (m^3)$$

For the whole drainage area- cylinder area A_c :

$$Q_t = A_c \times \int_0^t \frac{\partial q}{\partial t}\, dt \qquad (m^3) \qquad (37)$$

Substituting values of $\partial q/\partial t$ from Equation (36)

$$Q' = \left(\frac{16HA\ Rk}{\pi^2 M\rho g}\right)\int_0^t \left[\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^2}\left\{1-\exp\left(\frac{-(2n+1)^2\ \pi^2 Mt}{4H^2}\right)\right\}\right.\right.\times$$
$$\left.\left.\times\left\{\mathrm{Cos}\left(\frac{(2n+1)\pi z}{H}\right)\right\}\right]\right] \qquad (38)$$

Equation (38) gives the total oil expressed at any height z, from time t = 0 to any other time t and Q is in m^3.

At the exit point of oil from the rig z = 0 and hence

$$\mathrm{Cos}\left(\frac{(2n+1)\pi z}{H}\right) = 1$$

Equation (34) therefore, reduces to:

$$Q = \left(\frac{16HA\ Rk}{\pi^2 M\rho g}\right)\int_0^t \left[\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^2}\left\{1-\exp\left(\frac{-(2n+1)^2\ \pi^2 Mt}{4H^2}\right)\right\}\right)\right] dt$$

(39)

Integrating:

Putting: $$K_1 = \left(\frac{16HA_c Rk}{\pi^2 M\rho g}\right)\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^2}\right) \qquad (m^3/s)$$

and $$K_2 = \frac{(2n+1)^2\ \pi^2 M}{4H^2} \qquad (1/s)$$

$$\therefore \quad Q_t = K_1\left[\int_0^t dt - \int_0^t \exp(-K_2 t)dt\right]$$

$$= K_1\left\{\left[t\right]_0^t - \frac{1}{K_2}\left[\exp(-K_2 t\right]_0^t\right\}.$$

$$= K_1(t + (1/K_2)(1 - \exp(-K_2 t))) \qquad (m^3)$$

$$\therefore \quad Q_t = \left\{\frac{16HA\ Rk}{\pi^2 M\rho g}\right\}\left\{\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^2}\right)\left(t - \left(\frac{4H^2}{(2n+1)^2\ \pi^2 M}\right)\right. \right. \times$$

$$\left.\left.\left(1 - \exp\left(\frac{-(2n+1)^2\pi^2 M}{4H^2}\right)\right)\right)\right\} \qquad (m^3) \qquad (40)$$

Equation (40), therefore, gives the total oil expressed from time t = 0, to time t = t, when the rate of loading is R(Pa/s and cylinder area is A . Similarly for equation (34), and boundary and initial conditions:

when:

from $t = t_o$ - start of constant load expression, is (Equation (35)) at any height z is equal to:

$$u = u_o = \frac{16H^2R}{\pi^3\ M}\left\{\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^3}\left\{1 - \exp\left(\frac{-(2n+1)^2\pi^2\ Mt_o}{4H^2}\right)\right\}\times\right.\right.$$

$$\times\left\{\sin\left(\frac{(2n+1)\ \pi z}{H}\right)\right\}$$

the solution is given by the series:(Schiffman, 1958)

$$u(z,t) = \frac{16H^2R}{\pi^3 M}\left[\sum_{n=0}^{\infty}\frac{1}{(2n+1)^3}\left\{\text{Sin}\left(\frac{(2n+1)\pi z}{H}\right)\right\}\left\{1-\exp\left(\frac{-(2n+1)^2\pi^2 M t_o}{4H^2}\right)\right\}\times\right.$$

$$\left.\times\left\{\exp\left(-\left(\frac{(2n+1)^2\pi^2 M}{4H}\right)\left(t - t_o\right)\right)\right\}\right] \qquad \text{(Pa)} \qquad (41)$$

where t = time from start of expression (i.e including the period when the load was increasing at rate R, ($\partial\sigma_T/\partial t \neq 0$)

Solving for $\partial u/\partial z$ from equation (41) and substituting into equation (37) and integrating, total amount of oil expressed up to time t (including the initial period when the load is increasing) is obtained.

Simplifying Equation (41)

$$u(z,t) = \frac{16H^2R}{\pi^3 M}\left[\sum_{n=0}^{\infty}\left(\frac{1}{(2n+1)^3}\right)\left\{\text{Sin}\left(\frac{(2n+1)\pi z}{H}\right)\right\}\times\right.$$

$$\left.\times\left\{\exp\left(\frac{+(2n+1)^2\pi^2 M t_o}{4H^2}\right)-1\right\}\left\{\exp\left(\frac{-(2n+1)^2\pi^2 M t}{4H^2}\right)\right\}\right]$$

$$\therefore \quad \frac{\partial u}{\partial z} = \frac{16H^4R}{\pi^2 M}\left[\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\left\{\text{Cos}\left(\frac{(2n+1)\pi z}{H}\right)\right\}\left\{\exp\left(\frac{(2n+1)^2\pi^2 M t_o}{4H^2}\right)-1\right\}\right.$$

$$\left.\left\{\exp\left(-\left\{\frac{(2n+1)^2\pi^2 M t}{4H^2}\right\}\right)\right\}\right]$$

Substituting in equation (37) and integrating: at z = 0;

$$Q_t' = \frac{64H^3RA_c k}{\pi^4 M^2 g}\left[\sum_{n=0}^{\infty} \frac{1}{(2n+1)^4}\left\{\exp\left\{\frac{(2n+1)^2\pi^2 M t_o}{4H^2}\right\} - 1\right\} \times \right.$$

$$\left. \times\left\{1 - \exp\left(-\frac{(2n+1)^2\pi^2 M t}{4H^2}\right)\right\}\right] \quad (42)$$

Equations (40) gives the amount of oil expressed Q_t when the load is increasing at a rate R, while equation (42) gives the amount of oil expressed Q_t'' from time zero - (i.e. including the period when the load is increasing at rate R) for the times in excess of to - i.e. when the load is constant with time.

Taking Equations (40) and (42) and ignoring second order terms they reduce to: For Equation (40)

$$Q_t = K_1 \ (t + (1/K_2)(1 - \exp(-K_2 t))) \ (m^3) \quad (43)$$

$$\text{where } K_1 = \frac{16HA_c Rk}{\pi^2 M\rho g} \quad (44)$$

Units: (m^3/s)

and

$$K_2 = \frac{\pi^2 M}{4H^2} \quad (45)$$

Units (1/s).

and t = time in seconds.

and for Equation (42)

$$Q_t'' = K_3\left\{1 - \exp\left(-K_4 t\right)\right\} \qquad (46)$$

where
$$K_3 = \frac{64H^3RA_c k}{\pi^4 M^2 \rho g}\left\{\exp\left(\frac{\pi^2 M t_c}{4H}\right) - 1\right\} \qquad (47)$$

Units: (m^3)

and
$$K_4 = \frac{\pi^2 M}{4H^2} \qquad (48)$$

Units: (1/s)

and t = time in seconds.

In deriving equations (43) and (46) the area of oil flow has been taken as the whole cylinder area. This implies therefore, that the porous disc at the base of the cylinder does not offer any resistance to flow of oil through it. Thus, the effect of reducing the drainage area is to increase the drainage path H. However, if the drainage area is decreased to a level whereby there is resistance to oil flow through the porous disc then this resistance must be incorporated in the coefficient of permeability of the whole oilseed cake i.e. the situation will be similar to consolidation of a two layered soil column, with each layer having a different value for k-the coefficient of permeability This will be discussed further in section 6.4.2 when dealing with effect of varying the drainage area.

6.3. APPLICATION OF THEORY TO OIL EXPRESSION DATA.

Equations (43) and (46) are both non-linear equations. Although most of the parameters in the constants K_1, K_2, K_3, K_4 (equations 44, 45, 47 and 48) can be obtained experimentally two parameters namely M and k are not known and difficult to obtain experimentally for the compressible oilseed cake. Besides it has been assumed that both M and k are constants while in reality they will vary with time as expression proceeds and as the seed mass becomes more compact (section 6.2.1). It is necessary therefore to obtain average values of k and M in constants K_1, K_2, K_3 and K_4.

Because of the seemingly insoluble problem of obtaining quantitative data of k and M experimentally and their variation with time directly it was therefore decided to calculate average values for the constants K_1, K_2, K_3, K_4 from experimental data of Q_t the volume of oil expressed and t - time. Equations (43) and (46) were therefore assumed to be valid for the oil expression process and using experimental data of Q_t vst, the two equations were solved for the constants K_1, K_2, K_3, and K_4. A computer programme based on the method of Himmelblau (1972) for solving non-linear equations was used to solve equations (43) and (46) (see copy of programme in Appendix 3 together with model solution). The programme gave the best values of the constants K_1, K_2, K_3, K_4 to fit the experimental data of Q_t vst. These values of the constants were then substituted back into equations (43) and (46) and theoretical values of Q_t vs t were then calculated. Tables 15 and 16 give the computed values of constants K_1 - K_4 for rapeseed and cashew respectively for the drainage areas and loading rates used in the experimental data presented in Chapter 3. Fig. 40.- 47 show the theoretical and experimental results for Q_t vst for five drainage areas at a rate of loading R of 377.2 kPa/s (fig. 40 - 44) and four rates of loading R for one drainage area of 0.64% (Fig. 40, 45 - 47). for rapeseed. A table for theoretically calculated values of Q_t vst for cashew is presented in the Appendix 2 together with the computer programme (cf Table 7 in Chapter 3 for experimental data). As can be seen from Fig. 40 - 47 there is a reasonable agreement between theoretically calculated data of oil expressed with time and the experimental data. The following points are common to the comparison between theoretical and experimental data for both rapeseed and cashew:

(a) In all the cases the two equations (43) and (46) give different values for Q_t the oil expressed at time t_o - i.e., when the applied load changes from increasing at rate R kPa/s to a constant load i.e. R = 0. The Q_t value from equation (43) is higher in all the cases than the value obtained from equation (46) with the experimental value somewhere in between,

TABLE 15. COMPUTED VALUES OF CONSTANTS K_1(ml/s), K_2(1/s), K_3(ml), K_4 (1/s) IN EQUATIONS 43 and 46 AS CALCULATED FROM EXPRESSION DATA OF RAPESEED.

R = Rate of loading A_d= % Drainage area (% Drainage area (% of total cylinder area.

R→ / A↓	377.2Kpa/s				188.2 Kpa/s				94.3 Kpa/s				62.8 Kpa/s			
Constant	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4
0.64	0.376	0.126	71.2	0.0077	0.234	0.063	70.3	0.0043	0.126	0.037	71.9	0.0029	0.097	0.025	76.0	0.0024
1.85	0.289	0.148	61.4	0.0055	0.201	0.076	60.7	0.0036	0.090	0.042	61.8	0.0028	0.061	0.026	62.3	0.0020
3.60	0.120	0.190	31.4	0.0036	0.096	0.082	32.1	0.0030	0.056	0.048	32.3	0.0026	0.044	0.028	34.2	0.0018
5.70	0.111	0.220	27.9	0.0036	0.084	0.086	28.2	0.0026	0.044	0.055	29.4	0.0024	0.038	0.029	30.1	0.0017
8.30	0.092	0.240	27.0	0.0032	0.046	0.088	27.4	0.0024	0.036	0.062	27.2	0.0022	0.023	0.031	28.2	0.0016

TABLE 16: COMPUTED VALUES OF CONSTANTS K_1 (ml/s), K_2(l/s), K_3(ml) K_4 (l/s) AS CALCULATED FROM EXPRESSION DATA OF CASHEW.

R = Rate of loading kPa/s. A_d = Drainage Area (% of Total cylinder Area)

R → / A ↓	377.2 kPa/s				188.4 kPa/s				94.3 kPa/s				62.8 kPa/s			
Constant →	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4
0.64%	0.391	0.092	66.4	0.0096	0.196	0.058	73.2	0.0056	0.122	0.044	73.0	0.0037	0.096	0.035	77.0	0.0024
1.85%	0.298	0.109	59.0	0.0088	0.142	0.063	60.9	0.0042	0.097	0.049	59.0	0.0034	0.068	0.038	60.0	0.0022
3.60%	0.137	0.149	35.6	0.0049	0.106	0.071	31.4	0.0038	0.063	0.052	34.0	0.0031	0.047	0.041	31.2	0.0020
5.70%	0.108	0.194	30.4	0.0041	0.089	0.077	30.1	0.0031	0.050	0.059	30.3	0.0027	0.040	0.044	28.2	0.0019
8.30%	0.097	0.217	28.2	0.0038	0.052	0.082	.	0.0027	0.041	0.065	26.2	0.0023	0.031	0.048	26.4	0.0016

FIG. 40: THEORETICAL AND EXPERIMENTAL RESULTS FOR % OIL EXPRESSION (1000 /948) TIME FOR DRAINAGE AREA 0.64% AND LOADING RATE R = 377.2 kPa/s (RAPESEED)

Theoretical Equations: For t t : $Q = 0.376(t + (1/0.126)(1-\exp(-0.126t)))$ (ml).

For t t : $Q = 71.2\,(1-\exp(-0.0077t))$ Sample calculation in appendix 2 (d).

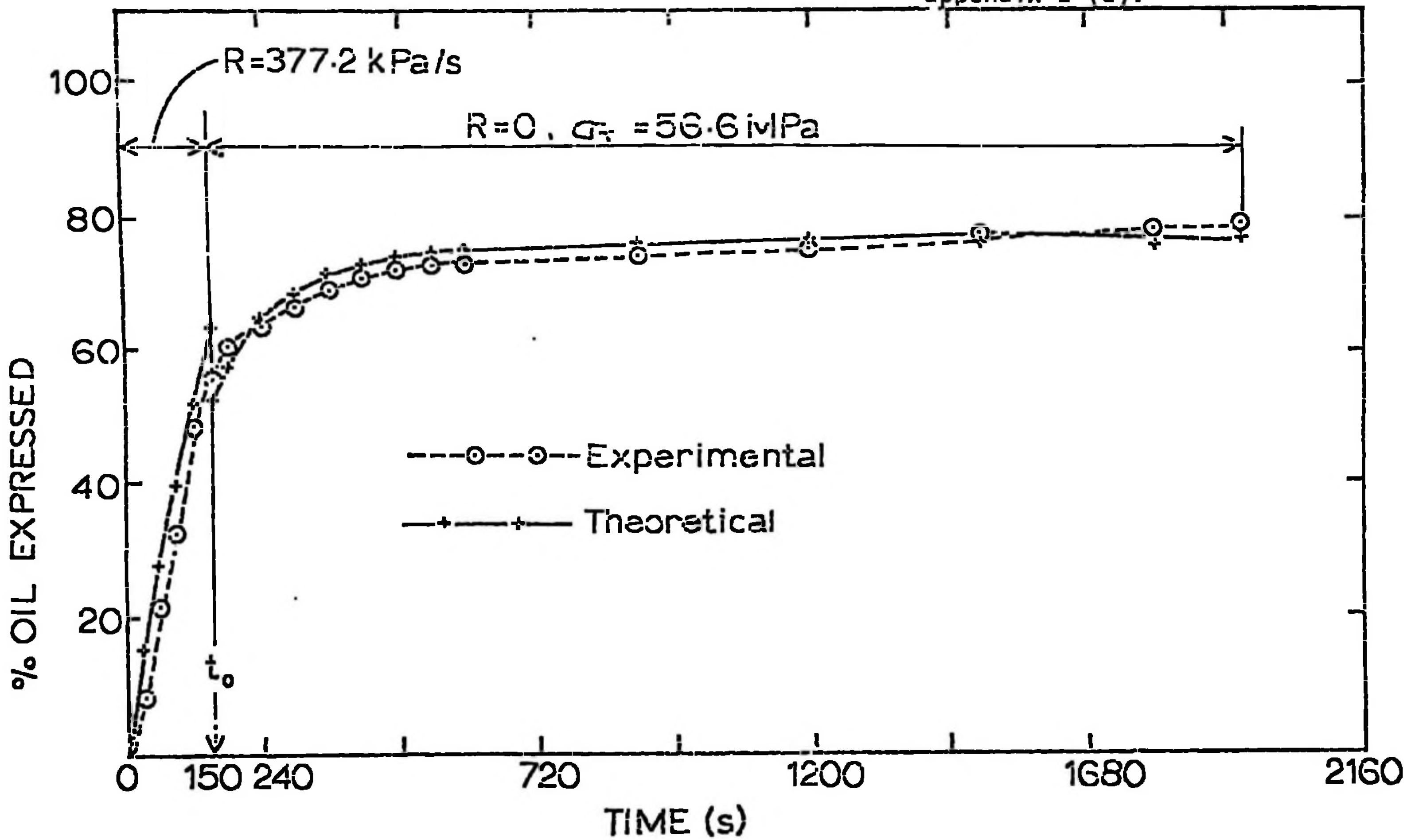


FIG. 41: EXPERIMENTAL AND THEORETICAL RESULTS OF % OIL EXPRESSED AGAINST TIME. FOR RAPESEED FOR DRAINAGE AREA 1.85% AND R = 377.2 kPa/s.

Equations for theoretical Results: For $t < t_o$: $Q_t = 0.289(t+(1/0.148) \times (1-\exp(-0.148t))$

For $t > t_o$: $Q_t = 61.4(1-\exp(0.0055t))$.

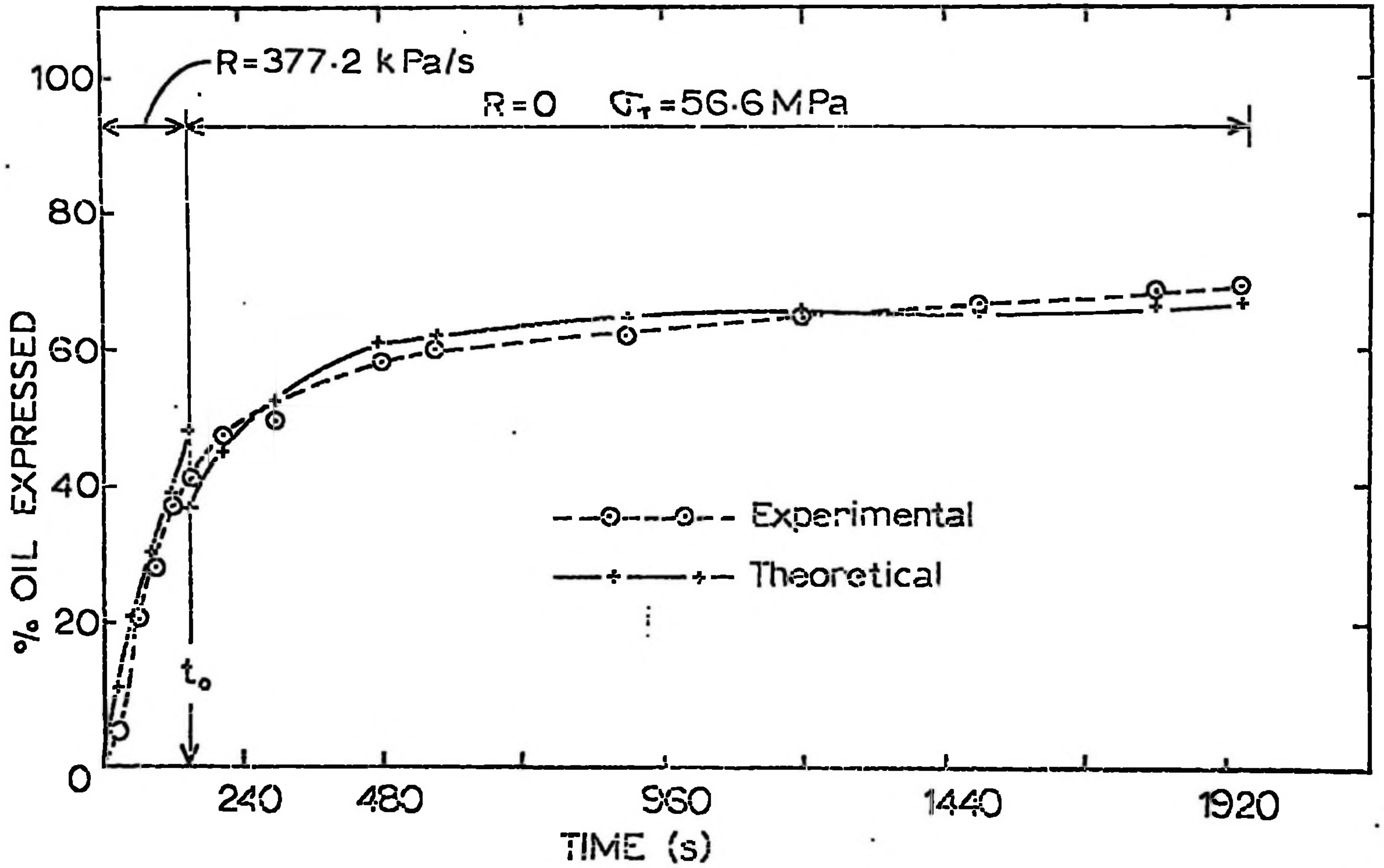


FIG. 42: THEORETICAL AND EXPERIMENTAL RESULTS FOR % OIL EXPRESSED AGAINST TIME FOR RAPESEED FOR LOADING RATE 377.2 kPa/s and DRAINAGE AREA 3.6%

Theoretical Equations: For $t < t_0$: $Q = 0.12(t+(1/0.19)(1-\exp(-0.19t)))$
For $t > t_0$: $Q = 31.4(1-\exp(-0.0036t))$

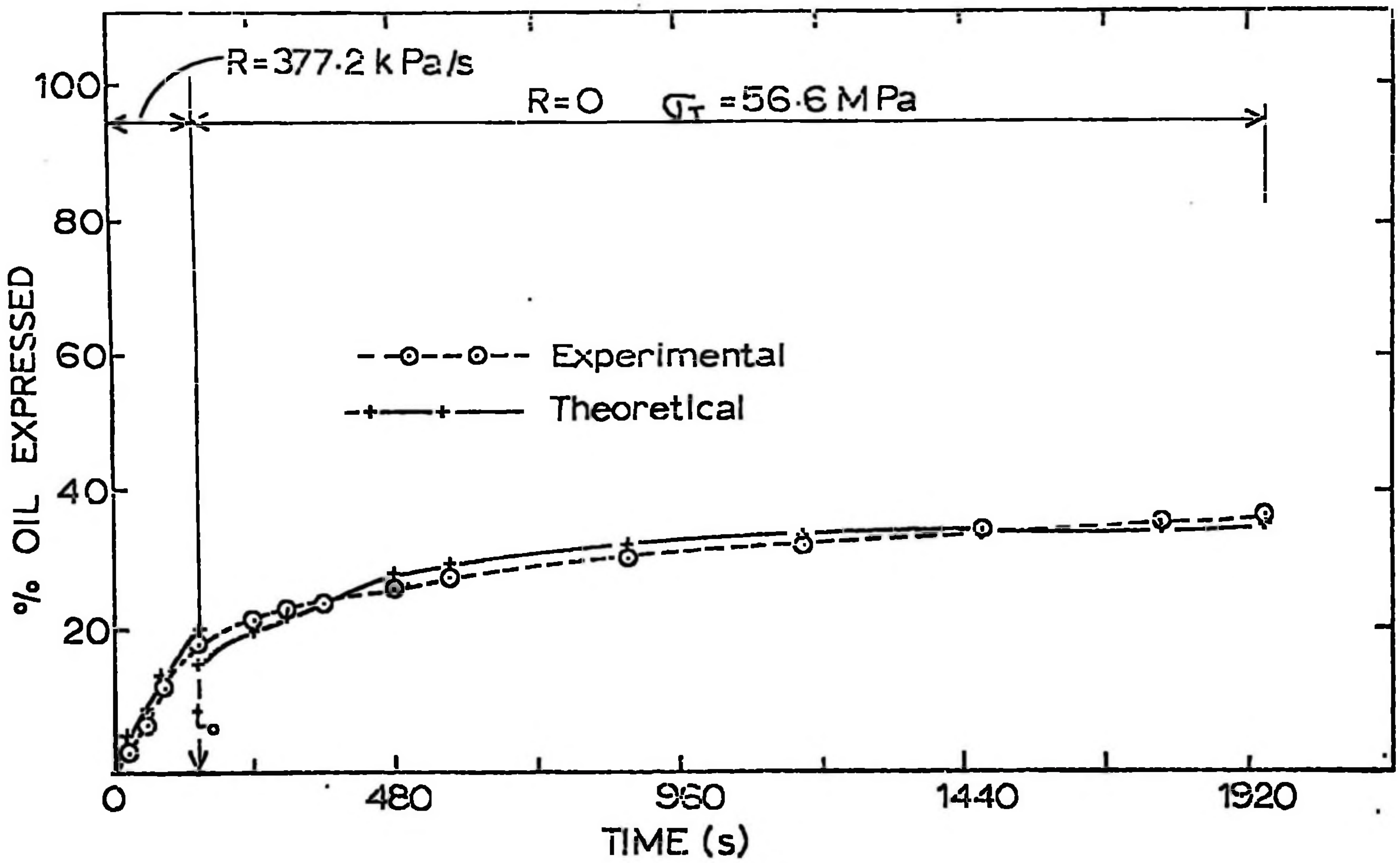


FIG. 43: THEORETICAL AND EXPERIMENTAL RESULTS OF ½ OIL EXPRESSED AGAINST TIME (t) FOR RAPESEED FOR DRAINAGE AREA 5.7% and R = 377.2 kPa/s.

Equations for theoretical results: For $t < t_0$: $Q_t = 0.11(t+(1/0.22)(1-\exp(-0.22t)))$ ml.
For $t > t_0$: $Q_t = 27.9\,(1-\exp(-0.0036t))$.

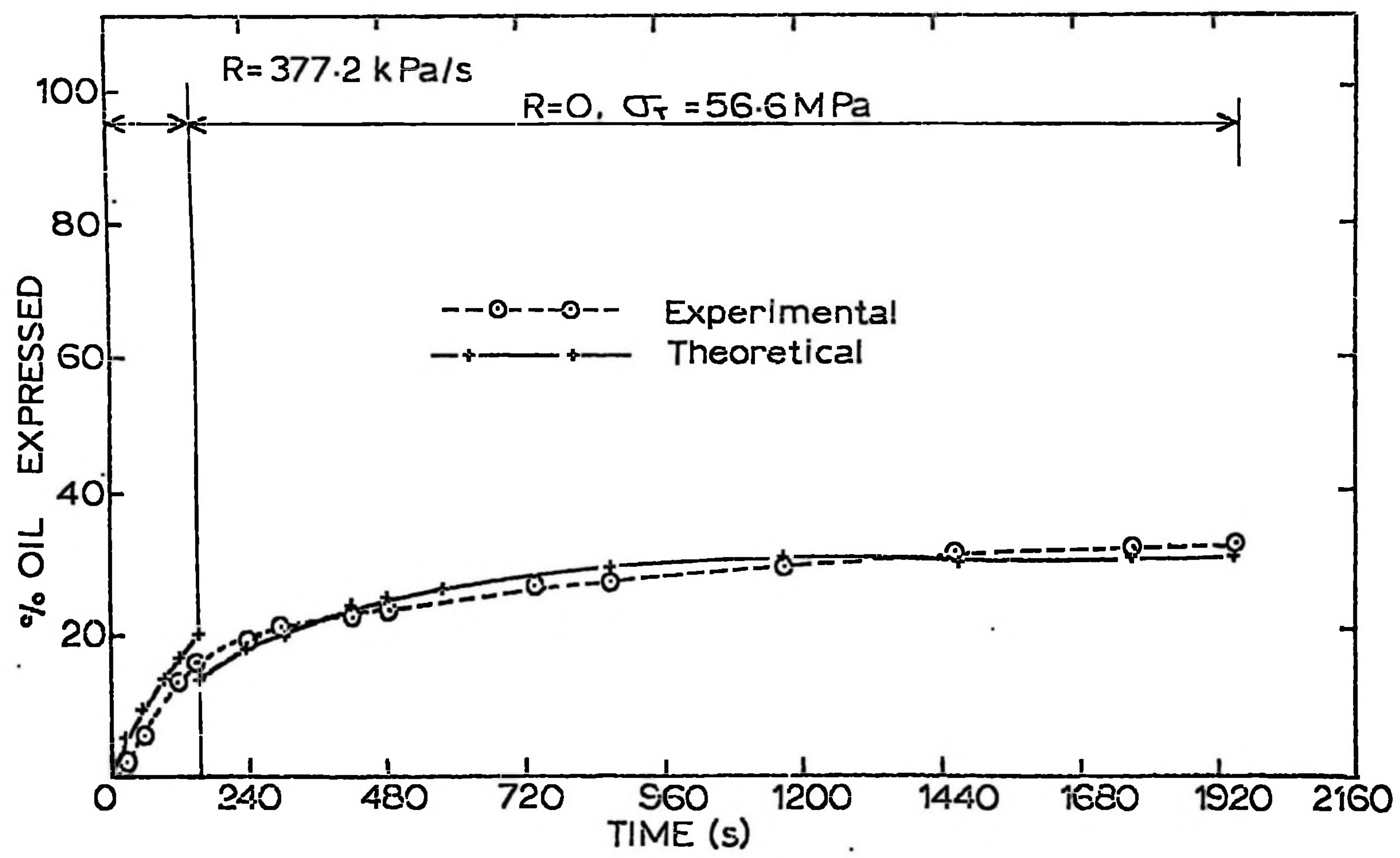


FIG. 44: THEORETICAL AND EXPERIMENTAL RESULTS OF % OIL EXPRESSED AGAINST TIME FOR RAPESEED FOR DRAINAGE AREA 8.3% AND R 377.2 kPa/s.

Theoretical equations: For $t < t_o$: $Q_t = 0.092(t+(1/0.24)(1-\exp(-0.24\ t)))$.
For $t > t_o$: $Q_t = 27.0(1-\exp(-0.0032t))$.

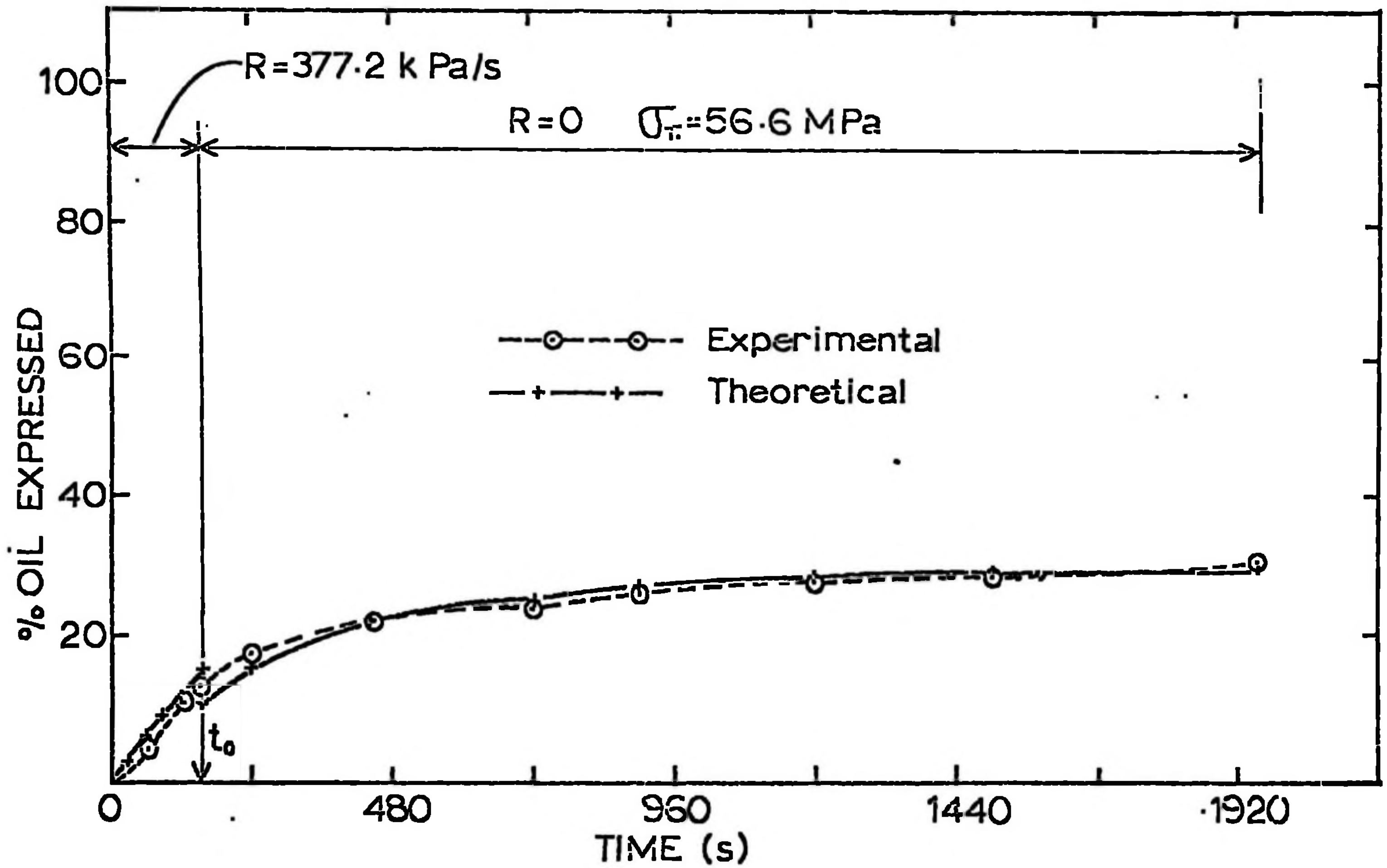


FIG: 45: THEORETICAL AND EXPERIMENTAL RESULTS FOR % OIL EXPRESSED AGAINST TIME (t) FOR DRAINAGE AREA = 0.64%, RATE OF LOADING = 188.4 kPa/s (RAPESEED).

Equations for theoretical Results: For $t < t_0$: $Q_t = 0.234(t+(1/0.063) \times (1-\exp(-0.063t)))$.

For $t > t_0$: $Q_t = 70.3\ (1-\exp(-0.0043t))$

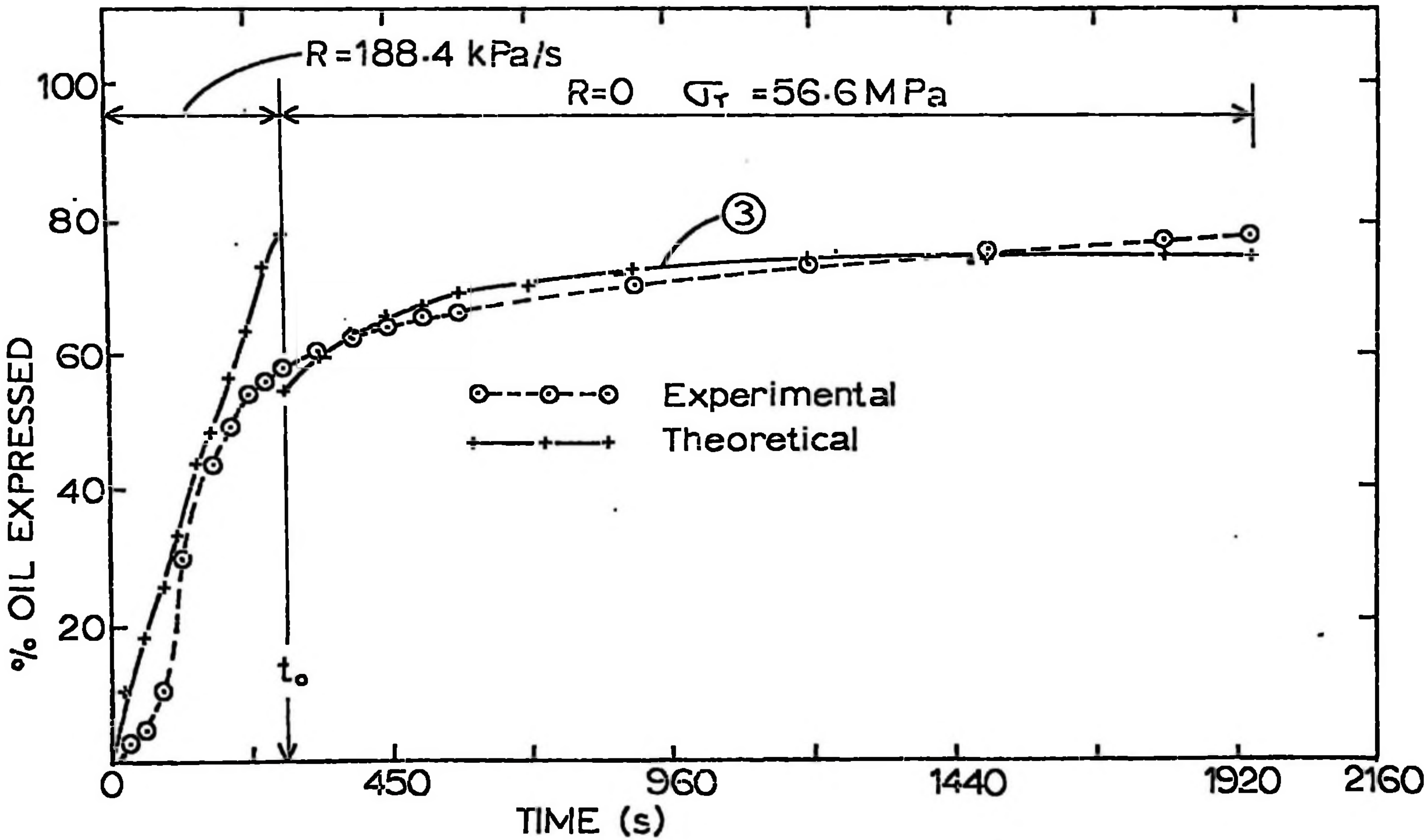


FIG. 46: THEORETICAL AND EXPERIMENTAL RESULTS OF % OIL EXPRESSED AGAINST TIME FOR RAPESEED AND FOR DRAINAGE AREA 0.64% AND LOADING RATE R = 94.3 kPa/s

Equations for Theoretical Results: For $t < t_0$: $Q_t = 0.126(t+(1/0.037)(1-\exp(-0.037t)))$
For $t > t_0$: $Q_t = 71.9\ (1-\exp(-0.0029t)$

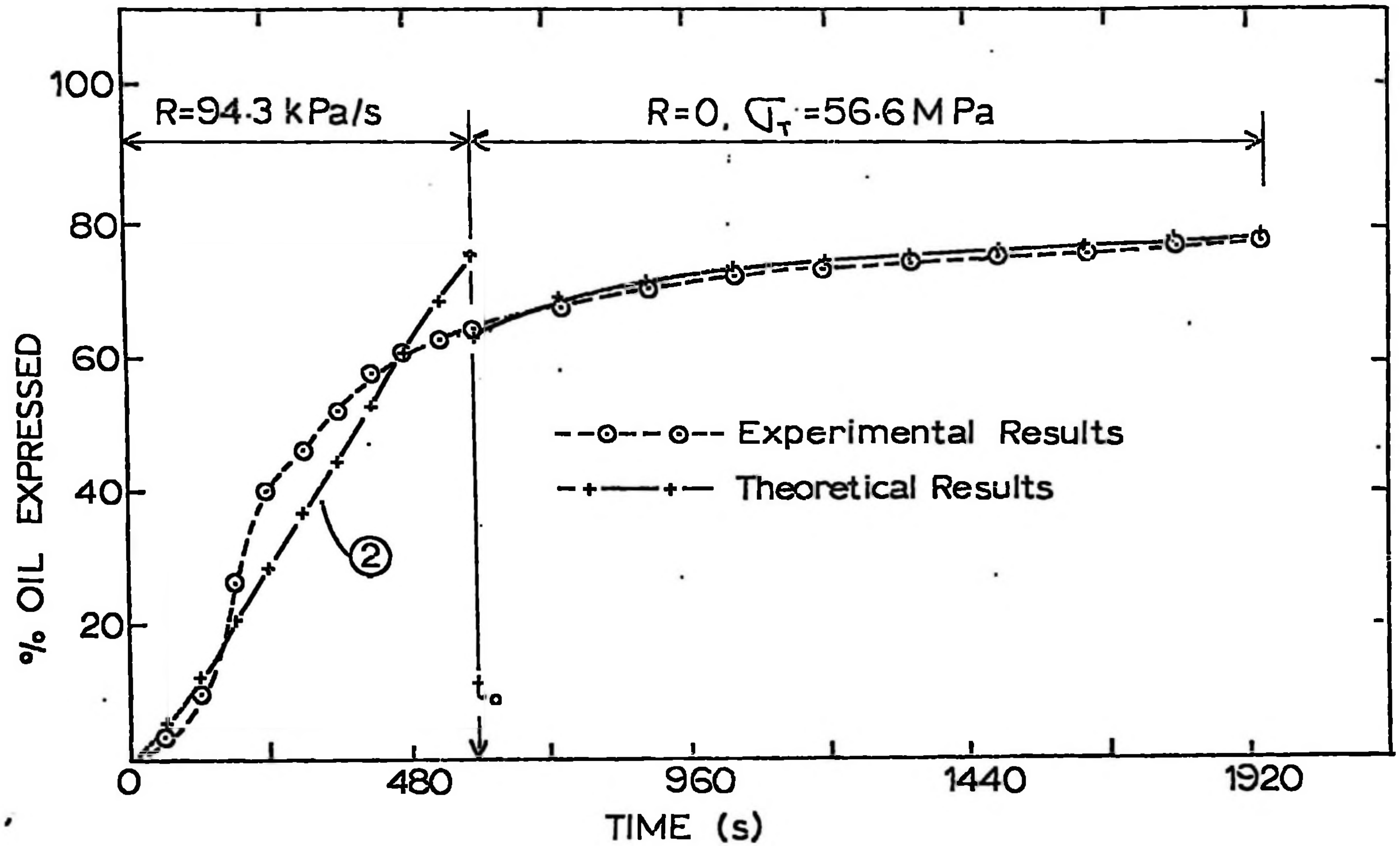
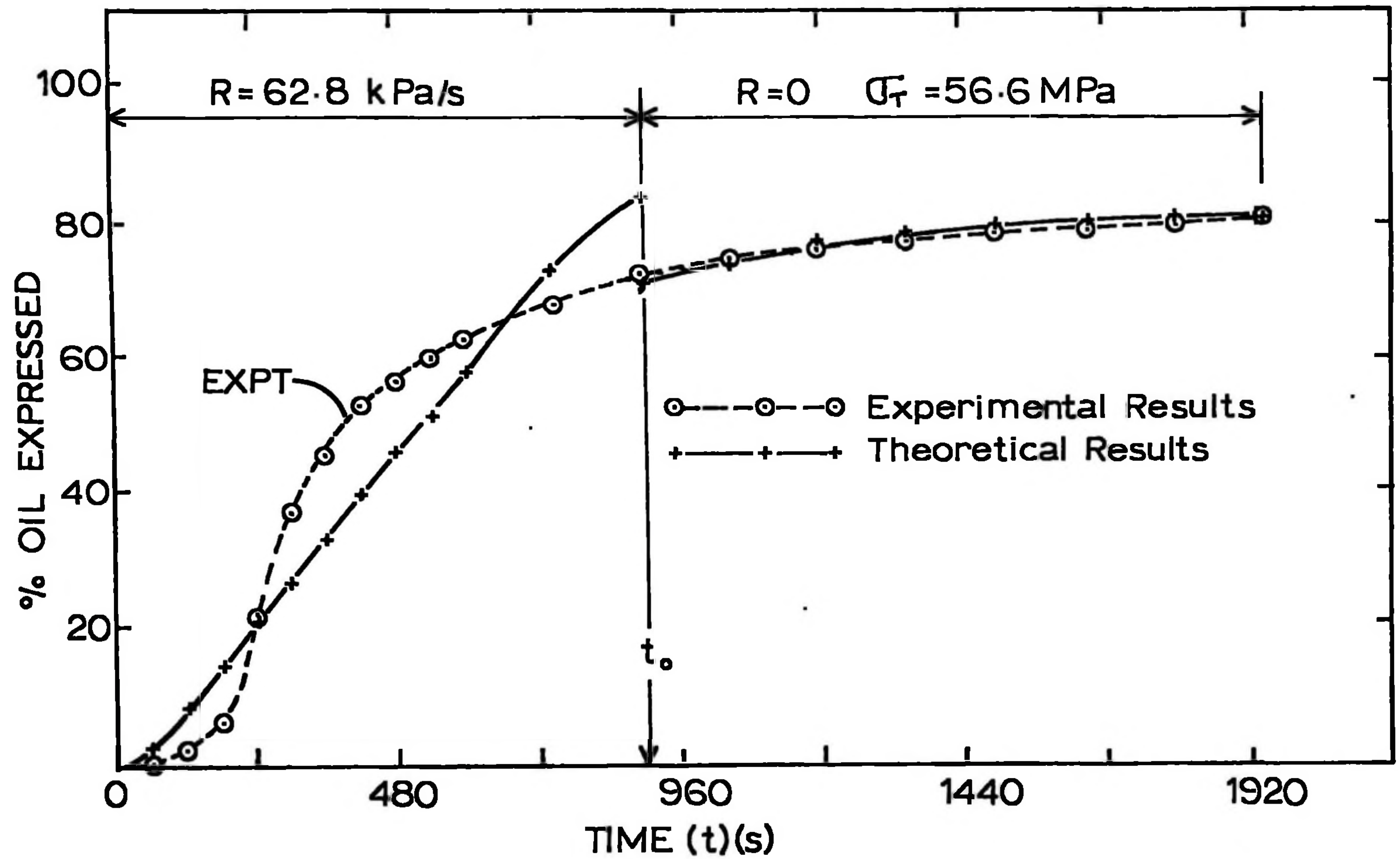


FIG.-47: THEORETICAL AND EXPERIMENTAL RESULTS OF % OIL EXPRESSED FROM RAPESEED FOR DRAINAGE 0.64% AND LOADING RATE 62.8 kPa/s.



nearer to the value of equation (46). Ideally the two equations are supposed to give the same value of Q_t at time t_o. As two equations are being fitted to one experimental curve, a discrepancy at the point of transition of the two equations ($t = t_o$) is inevitable. Secondly in computing the constants $K_1 - K_4$ two parameters which in actual sense vary with time are being averaged namely - k the coefficient of permeability and A_k the surface area of the kernels in contact with the intra-kernels voids. Initially when $t < t_o$, both A_k and k are large compared to their values when $t > t_o$ (when the seed kernels have been compacted and there is a greater resistance to oil flow through the intra-kernel voids.) Thus when $t = t_o$, there will be an over-estimation of Q. by equation (43) and an under-estimation by equation (46).

(b) From equations (45) and (48) $K_2 = K_4 = \pi^2 \; M/4H^2$. However, from tables 18 and 19 $K_2 > K_4$. In both cases of K_2 and K_4 it is only M which is likely to vary with time (as H the initial height of oilseed cake at t = 0 is a constant). From equations (28) and (32) the value of M is $(kV_i)/L_p'' n A_k \rho g)$. K_2 is computed from data when $t < t_o$ when both k and A_k are large, and K_4 is computed from data when $t > t_o$ when both k and A_k are small. It would appear, therefore, that the reduction in k is much greater than the reduction in A_k resulting in $K_2 > K_4$.

(c) The degree of agreement between data calculated from equation (43) and experimental data (i.e. when $t < t_o$) decreases as the rate of loading R decreases. For example for a rate of loading of 377.3 kPa/s there is reasonable agreement between data from equation (43) and experimental results (Fig. 40 for period when $t < t_o$) compared to a rate of loading of 63 kPa/s. (Fig. 47 when $t < t_o$). This will be discussed in greater detail when considering the effect of varying the rate of loading on equation 43 and 46. in section 6.4.1.

(d) The degree of agreement between equation (46) and experimental data was quite good in all the cases. (Fig. 40 - 47). Thus, even though equation 43 did not give a very good extimate of Q_t as explained in (c) above, quite good estimate of Q_t can be obtained by using equation 42 as this gives the total value of Q_t from time t = 0.

In general therefore, reasonable agreement was obtained between the theoretical model and experimental data with a few exceptions mentioned above. The effect of varying the experimental conditions on the theoretical models will be discussed.

6.4 EFFECT OF EXPERIMENTAL CONDITIONS ON OIL EXPRESSION BEHAVIOUR.

6.4.1 EFFECT OF VARYING RATE OF LOADING R.

Reducing the rate of loading initially leads to a reduction of the compaction rate of the seed kernels. This in turn reduces the initial flow of oil from within the seed kernels into the intra-kernel voids due to the lower values of σ_1 As a consequence the experimental curve is shifted to the right in the initial period compared to the theoretical curve where complete saturation and hence instantenous flow of oil is assumed. (cf Fig. 45 - 47).

Since the compaction rate of the seed kernels is lower, this in turn means A_k - the surface area of the seed kernels in contact with the intra-kernel voids changes more slowly in the lower rates of loading thus providing a larger surface area for oil to flow into the intra-kernel voids. As a result of this even though R decreases in equation 43 and 46, A_k increases and as a result of this there is little difference in the final amount of oil expressed when the loading rate changes. This is demonstrated by the experimental data at 1800s (Table 6 and 7) and theoretical data at the same time Fig.(45-47).

6.4.2. EFFECT OF VARYING THE DRAINAGE AREA.

6.4.2.1 Introduction.

In developing equations (43) and (46) the area used for calculating the total amount of oil expressed was the total cylinder area A_c. The effect of varying the drainage area was not directly incorporated into the equations. However, as the drainage area of the porous disc was not homogenous throughout the entire area of the disc (i.e. the porous discs with low drainage area were porous at the centre only Fig. 16) this led to a variation of the initial maximum drainage path H in the oilseed cake. The drainage area of the porous discs used in soil consolidation studies is uniform throughout the area of the discs. In this case, it is known that an increase in the initial maximum drainage path leads to an increase in the settlement and hence the amount of water expressed from the soils (Biot 1941). In screw expellers for oil expression the drainage barrel is made up of rectangular bars (of about 13 mm width) separated by spacing clips which provide drainage spaces of 0.25 mm for small seeds such as rapeseed, cottonseed, peanuts and soyabeans and 0.76 mm for larger and fibrous seeds such as copra (Norris 1964). This provides a drainage area of about 2 and 6% respectively of total area with the main objective being to provide a coarse filter for the oilseed cake. Thus the porosity or drainage area of the drainage barrell in a screw expeller is also not homogenous.

Due to the non-homogenity of the drainage area of the porous discs there is an increase in the initial maximum drainage path H, and secondly if the drainage area in the porous disc is reduced to very low levels, the resistance of oil flow through the disc becomes a significant parameter on the amount of oil expressed. There are three cases which can occur when the drainage area of the porous disc at the base is varied as discussed in the succeeding sections.

6.4.2.2. Resistance of the porous disc significant and drainage path increased.

If the drainage area is small (eg < 0.5% cf Fig. 16) there will be resistance to oil flow through the porous disc in addition to the resistance of oil flow through the intra-kernel voids. The situation then becomes analogous to two electrical resistors in series. Thus even though the drainage path is increased, and this should lead to more oil being expressed from the cake and reaching the porous disc (as will be explained in section 6.4.2.3) the resistance of the porous disc limits the amount of oil which can flow through it.

If the permeability of the oilseed cake is k and the permeability of the porous disc is k', then the total resistance to oil flow of the oilseed cake and porous disc is given by:

$$\text{total resistance} = \frac{1}{k_{eq}} = \frac{1}{k'} + \frac{1}{k} \qquad (49)$$

where k_{eq} = equivalent permeability of the oilseed cake and porous disc.

Thus the first case to be considered is for undrained compression. In this case k' = 0 and therefore, $1/k' = \infty$. This means there is no flow through the disc. If the drainage area is increased from zero, the permeability of the porous disc k' increases and in equation (49)the resistance to oil flow through the porous disc (1/k') decreases. This leads to the amount of oil which can flow through the disc increasing also. Thus in Fig.22 there is an increase in the amount of oil expressed as the drainage area increases from 0 - 0.5% at 1800s . There was a similar increase for all times (from t = 0) and all the loading rates used. (Table 6).

When the drainage area is increased further, k' the permeability of the porous slab becomes large and thus the resistance (1/k') of the porous disc approaches zero. In such a situation therefore, the increase in drainage path becomes the controlling parameter of the process.

6.4.2.3: Resistance of porous disc insignificant and drainage path increased.

Between 0.5 and 1.6% drainage area the resistance of the porous disc becomes insignificant. For a drainage area of 0.28 and 0.64%, the drainage path was constant but the area was different (Fig. 16: For a drainage area of 0.28 - there were 3 holes of a 2 mm diameter in circle 1 and one hole at the centre while for a drainage area of 0.64% there were 8 holes in circle 1 with one hole at the centre- thus the increase in initial drainage path for both cases was the horizontal distance from the edge of the cylinder to circle 1). The amount of oil expressed with these 2 drainage areas increased (Fig.22). However, when the drainage area was increased to 1.85% - the drainage path was 7mm less than in the 0.28% and 0.64% drainage areas (fig. 16) - the amount of oil expressed decreased sharply (Fig. 22). Thus in the region 0.5 to 1.5% the resistance of the porous disc becomes insignificant and the drainage path decrease leads to the amount of oil expressed decreasing instead of increasing due to the reduction of the drainage path (Fig. 22 and 16). The controlling parameter then becomes the variation of the initial drainage path H. In varying the drainage area from 0.64% to 3.6% the drainage path decreased by 14 mm (Fig. 16) while the amount of oil expressed at 1800s decreased from 78.4% to 35.3% for a loading rate of 377.2 kPa/s. (Table 6) for rapeseed (with a similar decrease at other times < 1800s). Similarly the theoretical results show that there is a corresponding decrease (Figs. 42 - 44) in the amount of oil expressed. This is so, because the amount of oil expressed Q (Equation 37) is directly related to the intra-kernel fluid pressure u, as follows:-

$$Q = A_c \int_0^t \frac{\partial q}{\partial t} dt$$

while $$\frac{\partial q}{\partial t} = \frac{k}{\rho g} \frac{\partial u}{\partial z}$$

while u is related to H as follows: for constant rate of loading expression:- (equation 35)

$$u(z,t) \propto H^2$$

and for constant load expression (equation 41)

$$u(z,t) \propto H^2 u_o$$

while u_o = pore pressure at the beginning of constant load period is $\propto H^2$ - (equation 41)

It follows therefore, that an increase in H, leads to an increase in Q - the amount of oil expressed. Secondly the experimental data showed an increase in the intra-kernel pore pressure, u, with a reduction of drainage area hence an increase in drainage path. (Fig. 24).

6.4.2.4. Increase in drainage path and area insignificant.

An increase in the drainage area (> 4% cf Fig. 22) with a consequent decrease in drainage path (fig.16) makes the effect of changing both parameters insignificant. The resistance of the porous disc to fluid flow is insignificant due to the large drainage area, and the increase in drainage path from the edge of the cylinder (Fig. 16) is small and has little effect on the amount of oil expressed. The drainage area of the porous disc is then almost homogenous (Fig 16) and the situation is then similar to soil consolidation where the porous disc has no effect on water flow in the soil mass. Thus the amount of oil expressed is independent of drainage area above 4% (Fig. 22).

6.4.2.5 Conclusion.

The experimental and theoretical results show that the drainage area is an important parameter affecting the oil expression process. With drainage areas between 0 to 0.5% the resistance of the porous slab is significant and the amount of oil expressed increases as the drainage area is increased. As the drainage area is increased further the resistance of the slab becomes insignificant while the corresponding increase in the initial maximum drainage path becomes the controlling parameter. Increasing the initial maximum drainage path leads to an increase in u - the intra-kernel fluid pressure and hence the amount of oil expressed. The maximum amount of oil is expressed when the drainage area is between 0.5 and 1.5%. Increasing the drainage area to greater values than 1.5% leads to a decrease in the drainage path and a corresponding decrease in the amount of oil expressed. A drainage area greater than 4% has little effect on the amount of oil expressed. The current machinery used in the oil industry have drainage areas between 2 - 6%. These could be reduced by maintaining the drainage spaces used (0.25 mm and 0.76mm) and increasing the width of the rectangular bars from 13 mm to 25 mm (giving a drainage area of 0.75%).

6.4.3.: EFFECT OF TEMPERATURE.

In chapter 5 the effect of temperature on the internal flow of oil was shown to be the increase in the hydraulic conductivity of the cellwalls. (i.e. by reduction of the viscosity).

Similarly for the intra-kernel flow, the coefficient of permeability is indirectly proportional to the viscosity as follows:(Lambe and Whitman 1969)

$$K_{T1} \nu_{T1} = K_{T2} \nu_{T2} \qquad (50)$$

Where $\nu_{T1\ T2}$ - viscosity at temperatures T_1 and T_2 respectively and $K_{T1\ T2}$ - permeability at temperatures T_1 and T_2

From Darcy's law:-

$$\frac{\partial q}{\partial t} = k \frac{\partial u}{\partial z}$$

It follows therefore, the rate of oil expression if temperature is increased from T_1 to T_2 will also increase $\left(\frac{\partial q}{\partial t}\right)_{T2} > \left(\frac{\partial q}{\partial t}\right)_{T1}$

and as a resutl more oil will be expressed. For example increasing the temperature from 20°C to 100°C decreases the viscosity coefficient from 0.84 poise to 0.094 poise (a 9 fold decrease). By equation 50 there is a ninefold increase in the coefficient of permeability and hence a corresponding increase in the rate of expression.

6.4.4. REDUCING SEEDSIZE AND RUPTURING CELLWALLS.

6.4.4.1. Introduction.

The experimental and theoretical results presented in Chapters 3 - 6 suggest that the bulk of the applied pressure is used for expression of oil from within the seed kernels into the intra-kernel voids. The internal flow depends on:

(a) the surface area of the kernels in contact with the intra-kernel voids A_k .

(b) the hydraulic conductivity of the cellwalls L_p' .

(c) the number of cellwalls the oil has to cross before reaching the intra-kernel voids n.

It was decided therefore, to vary the above three parameters by various mechanical pretreatments on the oilseeds before oil expression to test their effect on oil expression.

6.4.4.2. Reducing seedsize:

Rapeseed was ground to a powder (with 80% of the powder being of size between 300 μm and 600 μm and 20% between 600 m and 1200 m) using a laboratory grinder (Moulinex, Type 320). Oil was expressed from the ground rapeseed using the procedure outlined in section 3.3.2 with a drainage area of 1.85% and a loading rate of 377.2 kPa/s. The results of this test are shown in Figs 48 (Curve 2 in Fig. 48 for oil expressed compare with curve 1 for untreated seeds). It is seen that grinding the seeds, although it increases the surface area in contract with the intra-kernel voids A_k , and reduces n, the number of cellwalls the oil has to cross (both effects should lead to more oil being expressed from within the seed grains) it, however, greatly reduces the amount of oil expressed. This is due to the change in volume of the ground seeds which occurs almost instantenously on application of the load. This would appear to be the main factor contributing to less oil being expressed from ground seeds in that the small size of the seed grains makes it easier for them to be compacted almost instantenously a load is applied. As such the oil has less intra-kernel space to flow into.

6.4.4.3. Rupturing of Cellwalls.

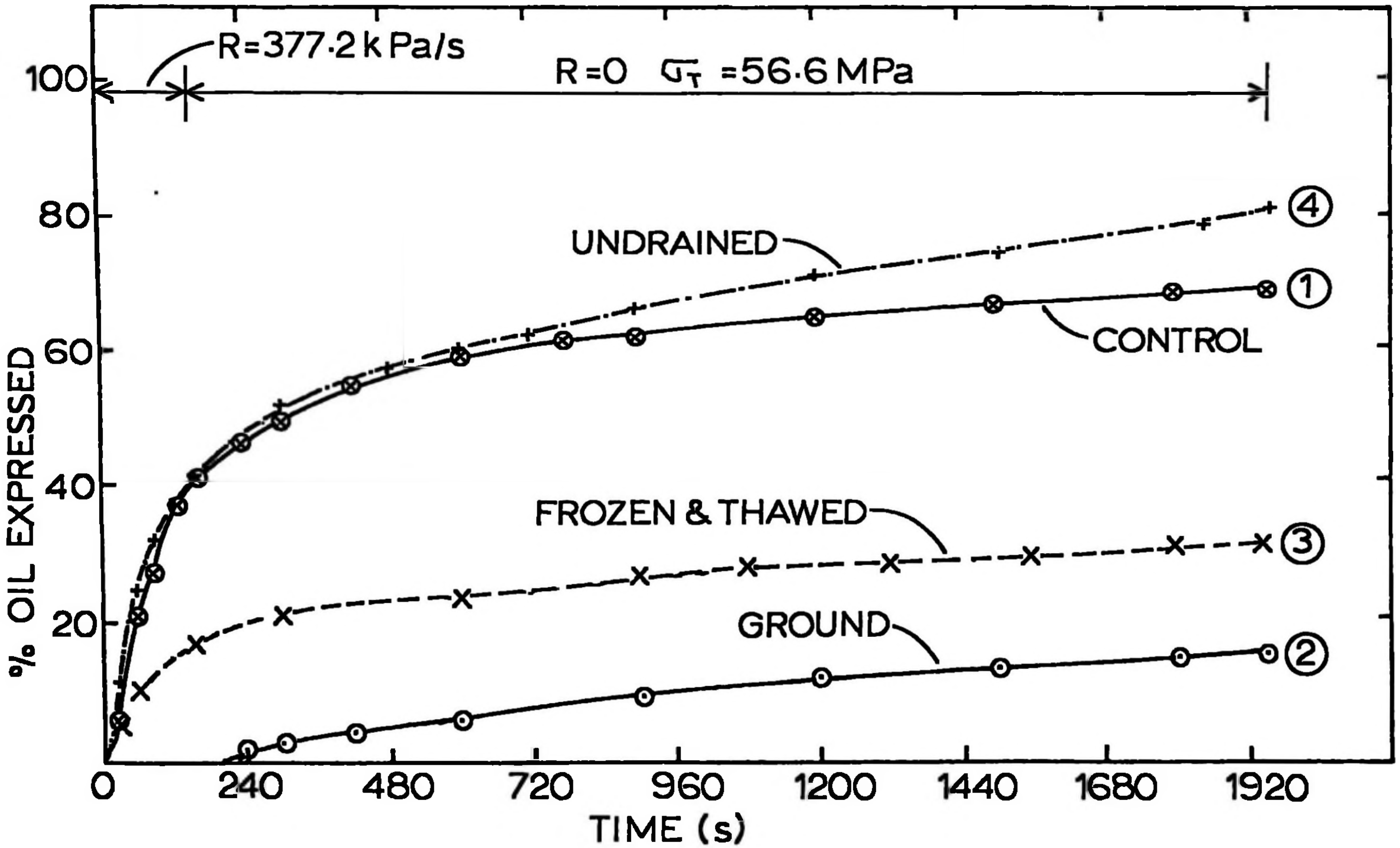
To rupture a substantial part of the cellwalls, the seeds have to be ground to ultrafine particles (< 20 μm diameter). This as explained already introduces the problem of reducing the permeability of the cake. The second method used in industry is to roll the seedsin rollers.However, Woolrich and Carpenter (1935) could observe little rupture of cellwalls in cottonseed rolled to thin flakes (1.5 mm). Secondly in studies on rupture properties of alfalfa cellwalls Koegel *et al* (1973,74) concluded that rolling did not rupture a substantial part of the cellwalls and they recommended instead extrusion through orifices. Also as discussed in Chapter 5, it is unlikely that rolling could rupture the cellwalls due to their porous nature. Extrusion through orifices on the other hand is unlikely to work with oilseeds as this would mix the oil and proteins and it would be more difficult to separate the two. Other methods therefore, had to be used to rupture the cellwalls and increase L_p.

(a) Freeze - Thawing Pretreatment.

Maekawa *et al* 1977 have reported that quick freezing and thawing in water of chlorella cells disintegrated 72% of their cellwalls. Frozen and thawed rapeseed (frozen in a deep freezer (-22°C) for 24 hours and

FIG. 48: EFFECT OF PRE-TREATMENT OF RAPESEED ON OIL EXPRESSION.

1- Control - Untreated - oil expressed at ambient temperature
2 - Ground to a powder. 3 - Frozen (- 24°C for 24 hrs and thawed.
4 - Undrained compression until σ_T = 45 MPa and oil expression as in 1 - 3
All cases: Drainage Area = 1.85%. Loading rate 377.2 kPa/s.



and thawed in a refrigerator (5^oC) for 48 hours and immediately pressed) yielded less oil when pressed than untreated seeds. (Curve 3 in Fig. 48). Although freezing and thawing could rupture water containing cells it is unlikely to rupture oil containing cells as most oils solidify between 3^o to -25^oC (rapeseed oil - 10^oC- cottonseed oil - 1^oC, peanut oil 3^oC (Weast (1974)). When oils solidify there is an increase in density of about 10 - 20% (Swern (1964). Thus, this reduction in volume of oil will compensate any increase in moisture volume when it solidifies.

(b) Microbiological methods.

Methods used in microbiology to rupture cellwalls of bacteria were applied to rapeseed:

(i) Grinding followed by mechanical impact:

The seeds were ground to less than 1200 μm diameter and placed in a Braun disintegrator together with glass beads (0.17 - 0.18 mm diameter and ratio of glass beads/seed 1:2). The principle of the Braun disintegrator is to agitate at high speed the beads and bacteria with the hope that by impact force the cellwalls will be ruptured. With oilseeds, however, this method proved ineffective as the seed particles were quite large for the impact forces to have any effect.

(ii) Sonication:

A sonicator was used on ground rapeseed in water. This method is widely used to rupture cellwalls of bacteria (Hussey 1979). However, the method had the effect of homogenizing the cell constituents and resulted in a homogenous mixture of oil, proteins and water which would be more difficult to separate by conventional mechanical expellers. It is possible, however, that using this method and then centrifuging the mixture to separate the oil, protein and water could prove successful. Further research will be required.

(c) Undrained compression followed by oil expression.

It was shown in section 3.3.5 that when both cashew and rapeseed were compressed without allowing the oil to drain out a pressure was reached (c_{Tr} = 28.5 MPa, for cashew and c_{TC} - 38.7 MPa for rapeseed) when the intra-kernel pore pressure u became equal to the applied pressure c_T. Scanning electron microscopic examination of cashew cells

compressed in this way revealed substantial cellwall rupture (section 4.4).This method was tried to see the effect on oil expression. A non-porous disc was placed at the base of the cylinder (Fig. 15) and a wire mesh was placed around the inside wall of the cylinder with two of the pore pressure holes left open. The oilseeds after being placed inside the wire mesh in the cylinder were pre-pressed as described in section 3.3.2.1.(a). Until oil was observed to come out of the pore pressure holes. These holes were then sealed and undrained compression was undertaken at a loading rate of 94.3 kPa/s until a load of 45 MPa (> 38.7 MPa) after which the load was immediately removed and the seeds emptied from the cylinder. The nonporous disc was changed to a porous disc (1.85% drainage area) and oil was expressed using the method outlined in sections 3.3.2.1 and 3.3.2.2 with a loading rate of 377.3 kPa/s until a load of 56.6 MPa and held there for 1800s. The results of this test are shown in Fig. 48 (Curve 4).
It is seen that the overall amount of oil expressed increases. (cf with untreated seeds curve (1)). Secondly the rate of expression is still high for undrained compressed seeds even at times in excess of 1800s. Thus, the effect of time is still

significant at times in excess of 1800s. The main reason for this is due to the rupture of the cellwalls. There is a substantial amount of inter-kernel flow of oil (due to the large pores on the cellwalls the oil does not flow into the intra-kernel and out of the seedcake, but flows from one kernel into another until out of the seedcake). Therefore the internal flow is not only into the intra-kernel voids but also into the adjacent kernels. The reduction of A and increase in n do not play a significant role in the expression process in this method.

6.4.4.4. Conclusion:

Grinding oilseeds reduces the permeability of the intra-kernel voids and as a consequence less oil is expressed. Freezing and thawing oilseeds does not rupture cellwalls due to the increase of density of the oil. Undrained compression followed by oil expression increased the amount of oil expressed. Other methods of rupturing cellwalls without reducing seedsize should be investigated. For example Boiko (1975) has reported that the simultaneous application of pressure and a high voltage pulse current increase water removal from clover five times compared to use of pressure only. Details of his method are not yet available.

6.5. CONCLUSION:

Oil expression process from cashew and rapeseed can be characterized by three fundamental equations

(a) a modified form of Terzaghi's equation to describe the behaviour of the consolidating oilseed bed.

(b) the Hagen- Poiseulle equation to describe the flow of oil through the porous cellwalls.

(c) Darcy's law to describe the bulk flow through the intra-kernel voids.

On the basis of these equations a partial differential equation has been developed to describe the expression process (equation 32 - $M\partial^2u/\partial z = \partial u/\partial t - \partial\sigma_T/\partial t$) This equation has been solved for the case of a linearly increasing load at rate R followed by a constant load regime. The theoretical solutions obtained have been compared with experimental results presented in Chapter 3. There is reasonable agreement between the theoretical model and experimental results. Effects of pre-treatment and varying experimental conditions on the mathematical model have been considered. These effects are incorporated in the mathematical model.

CHAPTER 7. DISCUSSION AND CONCLUSIONS.

7.1 INTRODUCTION.

In this section the mechanism of oil expression will be discussed and comparison will be made between the mathematical model presented in this study and the empirical equations developed by previous workers. The usefulness of the mathematical model in predicting oil expression will be considered together with a discussion on optimum strategy for oil expression.

7.2. MECHANISM OF OIL EXPRESSION.

Fig 49 is a qualitative model of the expression process. The first stage is common to both undrained compression (in which the seedcake is compressed without allowing the oil to flow out of it) and drained compression (in which the seedcake is compressed with the oil allowed to flow out - oil expression). Fig 50 and 51 show the different stages shown in Fig. 49 and variation of the different parameters (σ_T , u, σ_i) for undrained and drained compression respectively. In Fig. 49 it is assumed that the initial compaction of the seed kernels has occured, the bulk of air present in them has been expressed and the oil has been expressed into the intra-kernel voids with only a small fraction of their volume occupied by occluded air bubbles.

STAGE 1: At stage 1 oil expression has commenced into the intra-kernel voids from within the seed kernel and through the porous cellwalls. The air in the intra-kernel voids is occluded and a substantial part of it has dissolved in the oil. This occurs at an applied pressure of 9.05 and 3.54 MPa for rapeseed and cashew respectively.

7.2.1. UNDRAINED COMPRESSION.

STAGE 2. Between stages 1 - 2 the occluded air bubbles dissolve in the oil and a pressure build up commences in the oil in the intra-kernel voids. Thus the applied pressure is divided into two parts according to the modified form of Terzaghi's equation - σ_I - the kernel pressure and u the intra-kernel pore pressure (stage 2 and Fig. 26, 27 Chapter 3) with $\sigma_I > u$. Owing to $\sigma_I > u$ there is no equilibrium between the oil in the intra-kernel voids and the oil still in the cells within the seed kernel. In soil consolidation $\sigma_I = \sigma_e = 0$ and $u = \sigma_T$. The lack of equilibrium between the internal and intra-kernel oil leads to the cellwalls being under increasing tension $(\sigma_T - u)$.

STAGE 3. A further increase of the applied pressure leads to a stage whereby, the tension in the cellwalls

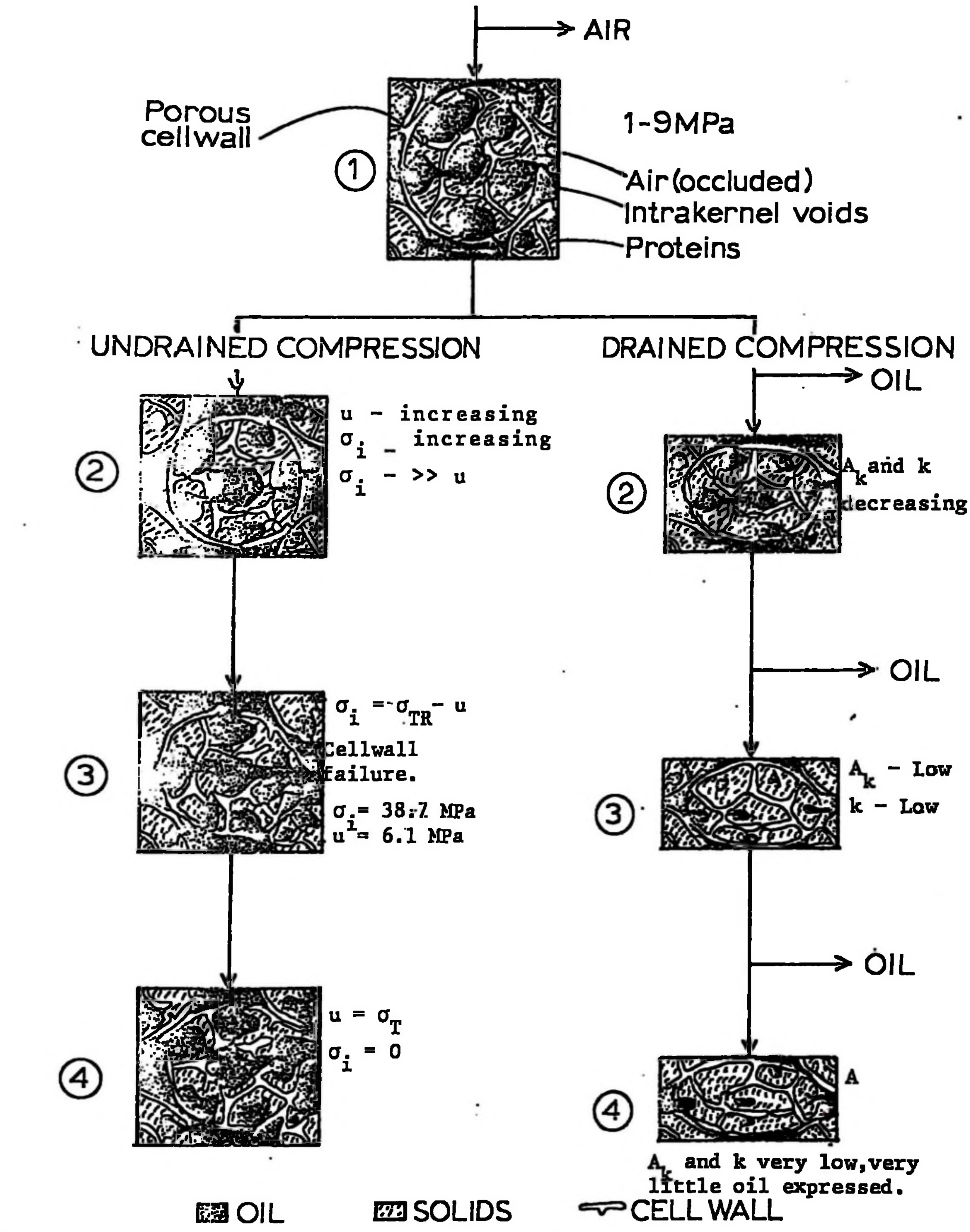


FIG: 49 A PHYSICAL MODEL OF THE OIL EXPRESSION PROCESS.

Stages 1 - 4 Ref to Text.

Undrained Compression:- Expression of oil from within seed kernels into intra-kernel voids but no oil expression from the oilseed cake.

Drained Compression: Expression of oil from seed kernels and out of oilseed cake. (oil expression).

For pressure ranges see Fig. 50 and 51.

is large enough to cause their failure and they are ruptured. As a consequence equilibrium is restored between the internal oil and intra-kernel oil and the pressure of the oil in the intra-kernel voids increases sharply (Fig.50).

<u>STAGE 4</u>: With equilibrium restored between the internal oil and intra-kernel oil, the oil pressure then becomes uniform throughout the seedcake and all the applied pressure is carried by the liquid phase. The situation is then analogous to the spring analogy in soil consolidation during undrained loading. The applied load at which equilibrium is restored in the oil pressures was shown in Fig. 28 to be σ'_{Tr} = 38.7 MPa and u_r' = 6.1 MPa for rapeseed and σ'_{TC} = 28.5 MPa and u_c' = 7.4 MPa for cashew, while the ruptured cellwalls were demonstrated for cashew in Fig. 35d. The pressures required to rupture the cellwalls is then equal to $\sigma'_{ir} = \sigma'_{Tr} - u$ which is equal to 32.6 MPa and 21.1 MPa for rapeseed and cashew respectively. The ratio of these pressures correspond reasonably well with cellwall dimensions presented in Chapter 4, if it is assumed that the pressures required to rupture the cellwalls will be proportional to cellwall thickness. Thus the ration $\sigma'_{ir}/\sigma'_{ic}$ = 1.84 while the ratio of cellwall thickness for rapeseed/ cashew - L_R/L_C = 1.59. It was also demonstrated in

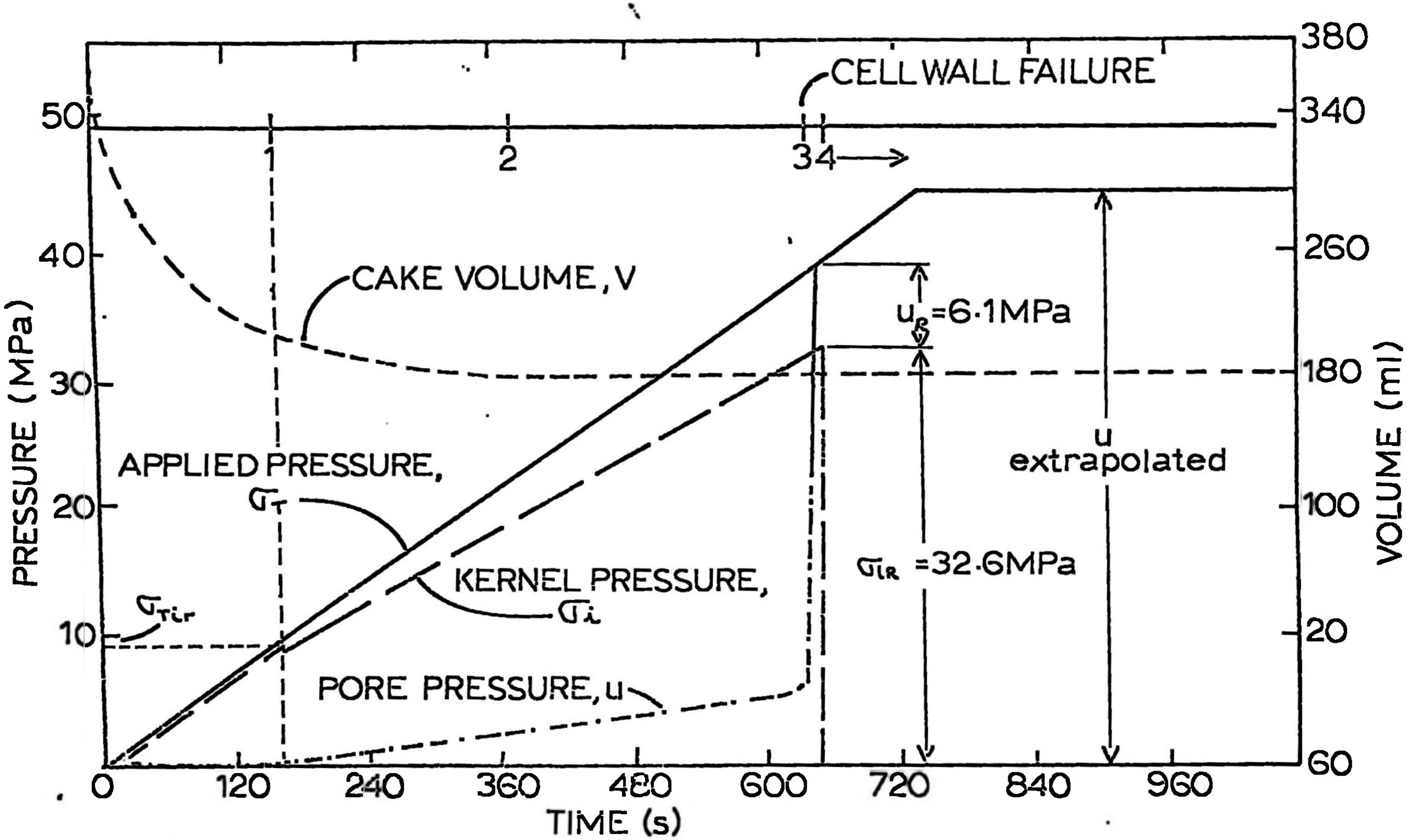


FIG. 50: VARIATION OF APPLIED PRESSURE (σ_T); KERNEL PRESSURE (σ_i), PORE PRESSURE (u) AND VOLUME OF OILSEED CAKE (200g) WITH TIME FOR RAPESEED DURING UNDRAINED COMPRESSION. Stages -1 - 4 refer to Fig. 49, u value extrapolated after 20 MPa

Chapter 6 (section 6.4.4 that rapeseed kernels which were compressed in undrained compression followed by oil expression yielded more oil than untreated seeds. (Fig. 48).

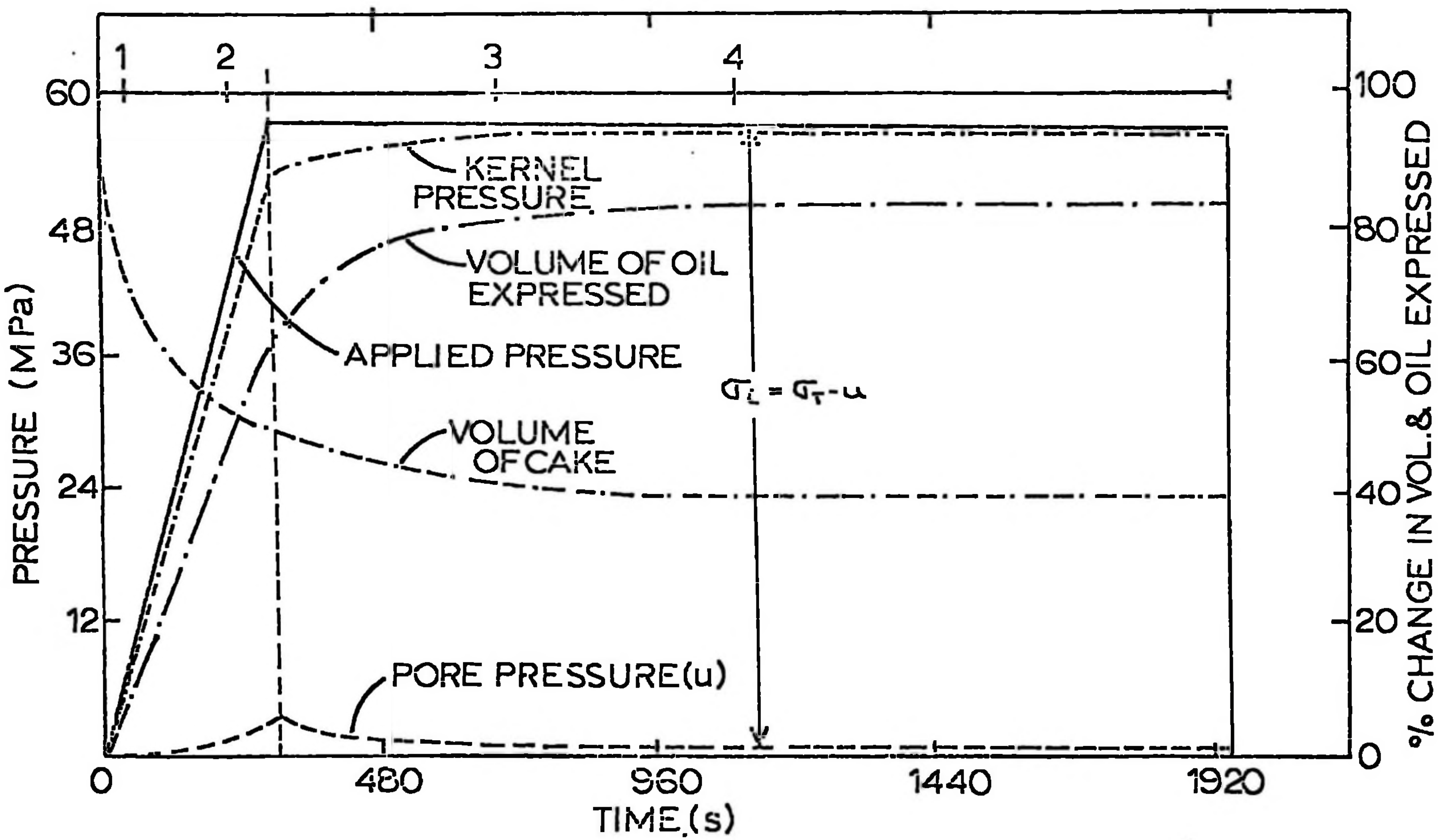
7.2.2. DRAINED COMPRESSION.

STAGE 2: During drained compression (oil expression) once oil expression commences into the intra-kernel voids, these fill up with oil and a pressure (u) build up in this oil commences. Oil expression out of the oilseed cake commences once u is large enough to overcome the resistance to oil flow of the oilseed cake and the resistance (if any of the porous disc at the base of the cylinder. A pressure gradient ($\partial u/\partial z$) is therefore, set up in the intra-kernel voids. Initially the intra-kernel voids are large 14.7% and 20.4% for cashew and rapeseed respectively (Table 5). As a consequence the surface area of the kernels (A) in contact with intra-kernel voids and the permeability (k) are both large. There is thus a large flow into the intra-kernel voids and if there is no resistance to oil flow at the porous disc the rate of flow out of the oilseed cake is high. (between stage 1 - 2 in Fig. 51).

STAGE 3: As the seed kernels lose more oil they are compacted and this results in a reduction of both

FIG. 51: VARIATION OF APPLIED PRESSURE (σ_T), KERNEL PRESSURE (σ_i) INTRA-KERNEL PORE PRESSURE (u) OIL EXPRESSED, AND CHANGE IN CAKE VOLUME WITH TIME FOR DRAINED COMPRESSION FOR RAPESEED.

Stages 1 - 4 Ref. Fig. 49.



A_k and k. As a consequence the flow of oil into the intra-kernel voids is decreasing and the resistance of flow through them is increasing. There is thus, a gradual reduction in the amount of oil being expressed from the oilseed cake (between stage 2-3 in Fig. 49 and 51).

STAGE 4. Owing to compaction of the seedcake both A_k and k are very low. Of the cells on the kernel surface only those in the area A_k (which is greatly reduced) are discharging oil into the intra-kernel voids. The rest of the cells are in contact with other seed kernels which are at an equal pressure (σ_i - kernel pressure) and hence there is no inter kernel flow of oil (i.e. flow from one kernel into another). The flow path in the seed kernel therefore, becomes tortuous and the oil has to cross a large number of cellwalls (with the consequent pressure losses) before reaching the intra-kernel voids through the surface area A_k. This coupled with the low permeability of the intra-kernel voids leads to a great reduction in the rate of oil expression (Stage 4 and after) and the expression Curve V_o (Fig. 51) is almost horizontal. If,however, the cellwalls were ruptured (Curve 4 Fig. 48) due to the larger pores on the cellwall, there is inter-kernel flow of oil and the rate of expression is still comparatively high even after 1800s of pressing.

7.3. COMPARISON WITH OTHER EXPRESSION MODELS.

As pointed out in Chapter 2 previous attempts at developing a mathematical model for the expression process have produced empirical equations from data obtained from the end point of the expression process rather than from the process itself. Thus the models of Koo(1942) (equation 1)' Baskerville *et al* 1947 (equation 2) and Gurnham and Masson (1946) (equation 3) were only useful in the prediction of oil expressed at times in excess of 30 minutes of pressing. Experimental evidence has shown that time is a significant parameter in the first 10 minutes of pressing. Secondly the physical meaning of the equations developed by Koo (1942) and Baskerville *et al* 1947 are difficult to discern. The effect of temperature was not well understood. For example Norris (1964) points out the primary objective of the cooking operation was to coagulate the proteins in the oilseed cells causing coalescence of the oil droplets. Experimental evidence on rapeseed and cashew has shown that oil can be expressed without the coagulation of the proteins and coalescence of the oil droplets by the action of heat.

The microstructure models used to develop the empirical equations assumed a non-porous cellwall and hence the need to rupture the cellwalls by mechanical forces before oil expression despite the fact that Woolrich

Carpenter (1935) could observe little disruption of cottonseed cellwalls rolled to thin flakes. Little disruption of cellwalls has also been observed in peanuts expressed by mechanical expeller (Vix et al 1972) and cottonseed with the oil extracted by solvent means (Hensarling et al 1970). These later observations have been confirmed in this study on rapeseed and cashew.

Studies on expression of plant juice protein from alfalfa leaves and stems by Koegel et al (1972, 1973a,b; 1974), Holdren et al (1972) have also produced empirical models based on data at the end point of the expression process. Koegel et al (1973) have divided the expression process into two parts - maceration, (rupturing of the cellwalls) and fractionation (expression of juice from macerated cells). In studies on maceration they conclude that rolling does not rupture a substantial part of the cellwalls and recommended extrusion through orifices. For the fractionation process although admitting that Darcy's law would be the most fundamental relationship to be applied they developed an empirical relationship (equation 4) because of the "seemingly insoluble problems in developing a mathematical model to predict the amount of liquid expressed from macerated alfalfa". Holdren et al (1972) have on the other hand based their empirical equation for the expression of juices from forages on on mass balance. Their equation (equation 5), was independent of such important expression parameters as applied pressure and pressing time and as such is of limited practical and theoretical value.

In the development of their empirical equations (Koo (1942), Baskerville _et al_ (1947) and Koegel _et al_ (1972,73) and later an Aboaba _et al_ (1972,73) have assumed that the applied pressure would be carried by the fluid part of the medium only. This assumption is wrong on the basis of the Terzaghi theory.

Swartzberg _et al_ (1977) divided the applied pressure into two components - a fluid pressure, and solid pressure. However in the computation of the fluid pressure they use an equation (equation 12) which cannot be correct in that the fluid pressure will be greater than the applied pressure.

Gustafson _et al_ (1977a,b) have used continuum mechanics principles to study the compression of a gas-solid-liquid media. Their main objective was to mathematically model the problems of cracking and splitting of the skins of biological materials such as fruits and vegetables prior to harvest and during harvesting. The solid phase is assumed to form a boundary between the liquid and gas phases

(Gustafson (1979)) and the two phases do not mix. This assumption makes their model inapplicable to the expression process. The expression model presented in this study has elucidated the basic mechanism of oil expression. The mechanism is shown to consist of two stages namely, the expression of the oil from the cells in a seed kernel through a porous cellwall into the intra-kernel voids and the final expression of the oil from the intra-kernel voids and out of the seedcake. The process has been mathematically modelled using three fundamental equations, modified Terzaghis equation, Hagen Poiseulle equation and Darcy's law. The physical parameters affecting the process i.e. temperature, drainage path and area, hydraulic conductivity of the cellwalls and permeability of the intra-kernel voids have been identified and incorporated in the model.

7.4. APPLICATION OF MATHEMATICAL MODEL TO PREDICTION OF OIL EXPRESSION.

The oil expression process has been characterised by three fundamental equations:

(a) a modified form of Terzaghi's equation to described the behaviour oilseed bed consolidation

(b) the Hagen Poiseulle equation to describe the flow of oil through the porous cellwalls.

(c) Darcy's law to describe the bulk flow through the intra-kernel voids.

From these equations a partial differential equation has been developed to describe the expression process: (equation 32)

$$M\ \partial^2 u/\partial z^2 = \partial u/\partial t - \partial \sigma_T/\partial t. \qquad (32)$$

M is a constant for a particular oilseed and is a function of the hydraulic conductivity, intra-kernel surface area A_k, coefficient of permeability of the intra-kernel voids, k, the number of cellwalls which the oil has to cross to reach the intra-kernel voids, and the specific gravity of the oil.

u = intra-kernel pore pressure.

z = co-ordinate height from drainage point of oil.

σ_T = total applied load.

To use the equation to predict oil expression for any expression machine, (expeller) the load variation of the machine has first to be obtained i.e. $\sigma_T = f(t)$. This is then partially differentiated with respect to time to get $\partial\sigma_T/\partial t$. The value of $\partial\sigma_T/\partial t$ is then substituted back into the partial differential Equation (32) and the equation is solved for u using the boundary conditions and initial conditions of the expeller. The solution obtained will give

$$u = f(\sigma_T, M, t, \text{boundary and initial conditions}).$$

This is then partially differentiated for $\partial u/\partial z$ and the value obtained is substituted into Darcy's Law

$$\partial q/\partial t = (k/\rho g)\ (\partial u/\partial z)$$

The value of k has to be obtained.

To get the total amount of oil expressed up to any time: use the integral:-

$$Q_t = \int_o^t \frac{\partial q}{\partial t}\ dt. \ \times \ \text{Area} \qquad (37)$$

To get the value of constant M, a laboratory test can be performed in a plunger/cylinder rig and Universal testing machine and collect data of Q_t - the volume of oil flow with time for the particular oilseed under study. With the aid of the computer programme in Appendix 3 an average value of M for the particular oilseed can be calculated. Alternatively an approximate value of M can be obtained by using the data of Q_t rst at two points and using either equations (43) or (46) depending on what time of expression one is considering (short times use equation (43) and long times use equation (46)) calculate the value of K_2, or K_4. From either of these, since the drainage path of the plunger/cylinder rig is known M can be calculated. ($K_2 = \pi^2 M/4H^2$) as shown below in 7.4.1. and k - the coefficient of the permeability is calculated from K_1 or K_3.

7.4.1. APPLICATION OF MATHEMATICAL MODEL TO A HYDRAULIC EXPELLER.

A typical pressing cycle in a hydraulic expeller is given as: (Norris 1964):

> Charging the press (feeding the oilseeds into the press) for 2 minutes, attaining maximum pressure 6 minutes, drainage time at maximum pressure 26 minutes, and discharging the press 2 minutes.

The presses are designed to exert pressures of 27.6 MPa - 31.0 MPa (4000 - 4500 psi).

The oilseed cake is wrapped in press cloths and placed in the press boxes (usually 1 press has 15 - 16 boxes). Standard size press boxes are 90 X 36 X 5 cm deep. It is required to predict the amount of oil expressed from one box at times 6,10,15,20,25,30,35 minutes for rapeseed.

From laboratory tests the following results of expression test are given:- from 200g of oilseed (rapeseed) (Table 6)

t(s)	300	600	900	1800
Q_t (ml)	46	56	58	64

and for a loading rate of 377.2 KPa/s until t = 150s. Since we are interested in the oil expressed after the load is constant (for hydraulic expellers the load is constant for a substantial part of the pressing operation) then equation (46) is applicable

$$Q_t = K_3(1-\exp(-K_4t)).$$

Using the experimental values of Q_t and t, values of K_4 can be computed by the computer programme as outlined in section 6 3. However, an approximation of K_4 can be obtained by solving for K_4 as done in Appendix 4. A value of K_4

can be obtained from each pair of data points. (i.e. for $t = 300, 600$; $t = 900, 1800$). These values are then averaged and as can be seen from Appendix 4, the value of K_4 obtained is fairly near the computed value. ($K_4 = 0.0044$ from Appendix, and $K_4 = 0.0055$ from Table 18). Using the average value or computed value of K_4, the value of M is then calculated using equation (48) - $K_4 = (\pi^2 M)/4H$, For the laboratory conditions. To get the value of k the coefficient of permeability of the intra-kernel voids, the value of K_3 on the laboratory test is taken as equal to Q when t is large. (equation 46). Thus, as all the other parameters in Equation (47) of K_3 are known k can be calculated. This is found to be 80.5×10^{-11} m/s forrapeseed. (See sample calculations in Appendix 4). The expeller conditions are then evaluated i.e. values of H, - equal to the height of the expeller box (5.1 cm), A_c = Area of press box = $3240 \times 10^{-4} m^2$, R = 76.6×10 N/ms t_D = 6 minutes = 360s and with values of M and k for rapeseed calculated from laboratory results K_3 and K_4 for the expeller can be calculated. Thus the equation of % oil expressed at ambient temperature on the hydraulic expeller:

$$Q_t = 48(1-\exp(-0.0044t)) \quad (51)$$

Values of Q_t vs t for rapeseed calculated by using this equation compare favourably with those given by Carter (1953) for hydraulic expeller.

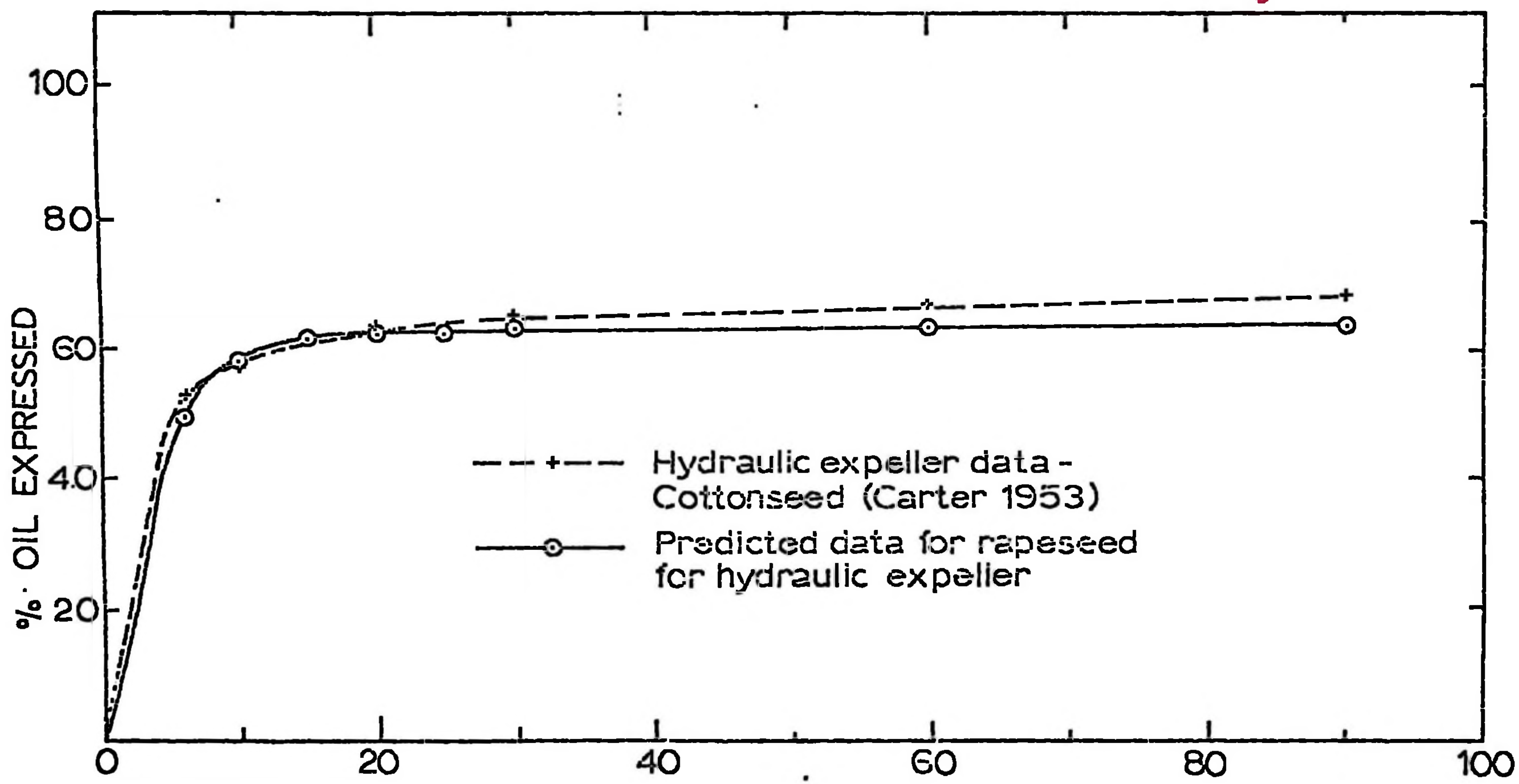
These are shown in Fig. 52 for:-

(a) Carter's 1953 results for cottonseed pressed at 90°C

(b) Theoretically calculated results using equation (46) at ambient temperature and corrected to 90°C using Fig. 11. See detailed calculations in Appendix 4.

FIG. 52: PREDICTION OF % OIL EXPRESSED IN A HYDRAULIC EXPELLER.

Comparison between theoretically calculated % oil expressed (equation 51) for rapeseed and experimental data from Carter (1953). Calculated values at ambient temperature and corrected to 90°C for comparison as in Appendix 4.



7.4.2. APPLICATION OF MATHEMATICAL MODEL TO A SCREW EXPELLER.

Detailed data for the rate of oil expression along the main shaft of a screw expeller are not available (Ward 1976). The mathematical model will be used to predict the oil expressed along a typical screw expeller, and the predicted final amount of oil expressed will be compared with experimental data. Thus, for a screw expeller for direct mechanical expression (Damien Croes Model SP50 - see details in Appendix 5) (Tindale and Hill Haas 1976). the following details are given:

Capacity = 59091 kg/24hrs

Cage length = 310 cm

Cage diameter = 22.5 cm X 20.0cm

Drive = 104.4 kw.

It is assumed that:-

(a) the drainage barrel - lower half of the barrel has bars 12.7 mm thick (Norris (1964) and as rapeseed is to be pressed the drainage spacing between the bars will be 0.25 mm.

(b) the maximum pressure on the cake will be equal to the maximum pressures in expellers which according to Norris (1964) is 232 MPa. It is assumed further that this pressure increases linearly along the length of the shaft from the feed end and reaching the maximum at the discharge end.

A mass of rapeseed is considered in it's progress through the screw press as one unit in a batch process and the mathematical model is applied to this mass.

The mass of the oilseed is obtained by taking the product of the volume available in the press (cf detailed calculation in Appendix (5)) and the density of rapeseed as determined in Chapter 3 (52.2 kg). From the capacity of the press, the feed rate is calculated as 0.68 kg/s and using these two values the residence time is 77 seconds. Values of M and k, for rapeseed are obtained from the laboratory test for a drainage area of 1.85% (drainage area of the screw press is 2%) (Table 6). (See detailed calculation in Appendix 5).

Since the load is assumed to increase linearly equation (43) applies. Thus, using the values of M and k as calculated for rapeseed and data on the screw press, K_1 and K_2 are calculated for the screw press as $K_1 = 29.2 \times 10^{-5}\ m^3/s$ and $K_2 = 0.51\ 1/s$ (Appendix (5)).

These values are used in equation (43)

$$Q_t = K_1(t+(1/K_2)\ (1 - \exp(-K_2 t)) \qquad (43)$$

to calculate the oil expressed in the Damien Croes SP50 expeller from time t = 0, to t = 77s when the cake is discharged from the expeller. (Appendis(5)). The predicted result shows that at the discharge end, 95% of the oil would be expressed.

According to Norris (1964) the objective of direct mechanical expression is to reduce the oil content down to 5-9% which corresponds reasonably with the predicted results.

7.5 OPTIMUM CONDITIONS FOR OIL EXPRESSION.

Examining the curve for % volume of oil expressed V_o in Fig. 51, the rate of expression ($\partial q/\partial t$) can be divided into 3 distinct regions:

(a) the initial region (stage 1 - 2) the rate of expression is high and for the higher rates of expression almost constant.

(b) the intermediate region (stage 2 - 3) when the rate of expression is falling.

(c) the final part (stage 3 - 4 and after) when the rate of expression is again constant but very low.

Over 90% of the oil expressed is expressed in the first two parts.

The experimental results show that less than 2% of the applied force is used for the flow of oil through the intra-kernel voids. The remaining part of the applied force is used to express the oil from within the seed kernels. Thus to optimize oil expression efforts should be directed at optimizing the internal flow. The flow of oil into the intra-kernel voids is dependent on the surface area of the seed kernels in contact with them and the hydraulic conductivity of the seed cellwalls. The surface area affects the pressure losses within the seed kernel. Thus initially at the commencement of expression A_k is large, . the flow path within the seed kernel is shorter and the oil has to cross fewer cellwalls. As a consequence pressure losses are lower and the rate of expression is high. As the seedmass is compacted A_k decreases and the flow path within the seed kernel becomes tortuous resulting in the oil crossing more cellwalls before reaching the intra-kernel voids. This results in a substantial part of the kernel pressure σ_i being lost in expressing oil through a tortuous path within the seed kernel.

It is desirable, therefore, for efficient oil expression to express as much oil as possible when Ak is large i.e. during the initial period. During this period the rate of internal flow will also depend on the rate of discharge of the oil from the intra-kernel voids. If there is a high rate of discharge from the intra-kernel voids the rate of internal flow will also be high. The rate of expression from the intra-kernel voids will depend on their permeability and pore pressure of the oil. Increasing the drainage path increases the pore pressure and as a result more oil is expressed. Thus, from the experimental data presented in Chapter 3 it is seen that maximum amount of oil is expressed when the drainage area is between 0.5 - 1.5% of the cylinder area. Machinery currently on market use drainage areas greater than this (Screw expeller 2 - 6.0%, Hydraulic expeller - a filter cloth is used to retain the cake during pressing and drainage area > 2%). There is need therefore, to reduce the drainage areas to the optimum drainage areas. Reducing the seedsize by grinding decreases the permeability of the intra-kernel voids and as a consequence less oil is expressed even though P_k and n are reduced. It is possible, however, if ultrafine grinding is done (particles less than the average cell diameter) and then use centifugation for separation of the oil from the solids could lead to a better method of oil extraction.

Experimental results show that if undrained compression is done on the seeds until cellwall failure and then oil expressed from these seeds more oil is expressed than from untreated seeds. Thus instead of precrushing the seeds by rolling as is done in industry, a method could be devised to compress the seeds in a confined space before the final expression.

In recommendations for efficiency oil expression Carter (1953) and Hickox (1954) reported that there was no advantage to be gained in pressing oil seeds for longer than 35 minutes. Their recommendation was based on data as reviewed in Chapter 2 of pressing at longer times. From the experimental evidence presented in Chapter 3 it can be said that the amount of oil expressed after 10 minutes is very small and it is recommended expression should not take more than 10 minutes.

7.6 CONCLUSIONS.

1. The conventional theory of oil expression from vegetable oilseeds suggests that before substantial oil expression can occur, the oilseed cellwalls must be ruptured by a combination of physical (by crushing) and thermal (cooking) treatments. Results from this study show that oil is expressed through a porous cellular microstructure without cellwall rupture. Expression tests on whole rapeseed and cashew kernels have revealed that up to 80% oil can be expressed without any physical or thermal pre-treatment at ambient temperature. The porous microsturcture of both cashew and rapeseed has been confirmed by transmission electron microscopy. These pores which are the main channels through which oil is expressed from the seed cell are of diameter 0.87 and 0.126 μm and the average porosity of the cellwalls was 0.093 and 0.171% for rapeseed and cashew respectively.

2. Expression tests at 20°C - 140°C and at constant rate of strain (0·1 - 2 mm/min) for both rapeseed and cashew led to the following conclusions in relation to the extent and rate of oil expression:

   a) The rate of oil expression is insignificant at pressures above 25 MPa at 20° - 140°C in relation to increasing the extent of oil expression.

(b) At loading rates of 0.1 and 2 mm/min the extents of oil expression at 20^{o}C were 70 - 75% and 50 - 55% respectively and the times required were 140 and 7 minutes respectively. Therefore, it is better to load at rates of 2mm/min of greater because the rate of expression is much faster than the reduction in the extent of oil expressed.

(c) In all cases higher temperatures increase both the rate and extent of oil expression due to the reduction in oil viscosity rather than cellwall rupture.

3. Expression tests at 20^{o}C and at constant rate of loading (63 - 377 kPa/s) followed by constant load (57 MPa) for both rapeseed and cashew have led to the following conclusions:

(a) The optimum rate and extent of oil expression occured a drainage area of between 0.5% and 1.5%.

(b) Higher rates of loading greatly increased the initial rate and extent of oil expression.

(c) Subjecting the oilseeds to freeze - thaw and grinding pre-treatments reduced both the rate and extent of oil expression. However, undrained compression to pressures greater than 30 MPa and 40 MPa for cashew and rapeseed respectively, followed by oil expression increased both the rate and extent of oil expression. This was due to cellwall rupture observed in electron micrographs.

4. The mechanism of oil expression was succesfully described by a mathematical model based on three fundamental equations i.e.

(a) A modified form of Terzaghi's equation for the consolidation of saturated soils to describe the behaviour of the consolidationg oilseed cake.

(b) The Hagen Poiseulle equation of flow of fluids through pipes to describe the flow of oil through the porous cellwalls within the seed kernel and into the intra-kernel voids.

(c) Darcy's law of flow of fluids in porous media to describe the flow of oil through the intra-kernel voids to the outside of the oil-seed cake.

The mathematical model has been successfully applied to the experimental data and the following were identified as the controlling parameters of the rate and extent of oil expression: the hydraulic conductivity of the pores on the cellwall; the number of cellwalls within the seed kernel the oil has to cross before reaching the intra-kernel voids-; the surface area of the seed kernels in contact with the intra-kernel voids-; the

the intra-kernel fluid pressure; and the permeability of the intra-kernel voids.

5) The mathematical model was successfully applied to predict oil expression in hydraulic and screw expellers. It is recommended that the drainage areas in screw expellers should be decreased from the current 2.6% to the optimum drainage areas of 0.5% - 1.5%.

6. Experimental and theoretical observations have led to the formulation of an optimum strategy of oil expression in two cases:

Case 1: Where mechanical expression followed by solvent extraction is used (normally used for high oil (>25%) content seeds): The physical (pre-crushing) and thermal (cooking) pre-treatments are not required. In addition pressing should not take longer than ten minutes. Instead the oilseeds should be pressed directly with the drainage areas in the expellers reduced to the optimum drainage areas (0.5 - 1.5%). Up to 80% of the oil present in high oil content seeds can be extracted in this way leaving the remainder to be extracted by solvent extractors.

Case 11. Where mechanical expression is the sole method: (for high or low oil content seeds): Rolling or grinding does not rupture the cellwalls. It is recommended, therefore, this physical pre-treatment should be replaced by an undrained compression pretreatment. The thermal pre-preatment should be retained and the oil should be expressed with the drainage area in the expeller reduced to the optimum drainage area.

7.7 RECOMMENDATIONS FOR FUTURE RESEARCH.

1)The universality of the mathematical model presented in this study should be tested on oilseeds other than rapeseed and cashew, in particular low oil content oilseeds for determination of general design criteria of oil expression equipment for all oilseeds. The presence of plasmodesmata in cottonseed, soyabeans peanuts, and palm kernels has been confirmed by Vix et al (1972) Diekert and Diekert (1972,1976) and Carr (1976). Thus, the same procedure as used in this study could be used for the other oilseeds.

2) The mathematical model developed in this study to describe the expression process should be solved for other types of loading histories (non-linear) in order to determine the optimum loading regime for oil expression.

3) Simpler methods of determining the constants M- describing the compressibility of the seed kernels - and hence rate of internal oil flow from the seed kernels, and k the coefficient of permeability of the intra-kernel voids appearing in the mathematical model other than the computer programme used in this study should be investigated. Obtaining such data by simpler methods should enable machine operators to determine the optimum strategy of

expressing oil from new oilseeds if the mathematical model is applicable.

4) The recommended improvements in the design of screw expellers (i.e. reducing drainage area, and having a high pressure undrained compression chamber before the drainage barrel for rupturing cellwalls) should be investigated experimentally.

5) New methods of pre-treatment of oilseeds and oil expression should be investigated experimentally to determine if they are more efficient than the conventional oil expression methods. In particular the following methods should be investigated:

a) Ultra-fine grinding (to less than cellsize) and separation of the oil by centrifugation.
b) Rupturing of cellwalls by sonication and separation by centrifugation.
c) Simultaneous application of pressure and high voltage current as reported by Boiko (1975) to have increased water removal from clover by five times compared to the use of pressure only.
d) Expression at higher moisture content than the currently recommended moisture contents of 3 - 5% (Anderson 1976), for best efficiency in expression. If oil could be expressed at higher moisture content without reducing the

efficiency of the expression process than this would save drying costs.

A P P E N D I C E S

APPENDIX 1. HIGH TEMPERATURE TESTS MOISTURE CORRECTION FACTORS (SECTION 3.2.3.4):

(a) OIL EXPRESSED and MOISTURE CORRECTION FACTOR FOR ELEVATED TEMPERATURE TESTS (SECTION 3.2.3.4) FOR CASHEW.

Temperature °C	Oil expressed from 30g of Cashew (g)			Average value	Moisture correct-factor(g)	Oil expressed %
	1	2	3			
20	6.13	6.00	6.29	6.12	0.0	49.17
40	6.94	6.80	7.02	6.92	0.10	54.78
60	7.32	7.40	7.18	7.30	0.18	57.19
70	8.01	7.92	7.86	7.93	0.25	61.69
80	8.83	8.40	3.32	8.52	0.40	65.22
90	9.68	9.52	9.63	9.61	0.60	73.09
100	10.30	10.18	10.44	10.31	0.72	76.39
110	10.77	10.89	10.56	10.74	0.84	79.52
120	10.81	10.76	10.91	10.83	0.90	79.89
130	10.88	11.02	11.12	11.01	1.05	80.00
140	11.52	11.92	11.34	11.35	1.12	82.17

Loading rate 0.2 cm/min - x-head speed. Load raised to 4500Kg and then stopped and immediately dropped to 0 in all above tests. Temperature raised from 20°C to desired temperature, after that desired temperature maintained for 1 hour and seeds transferred to oil expression rig and expression commenced immediately at above mentioned expression rate. Loss in weight determined by weighing after expression. Moisture correction factor obtained as explained in experimental methods. Amount of oil remaining in expressed cake checked by Soxhlet method and was found to be quite near the above results (0.5% experimental error).

(b) OIL EXPRESSED AND MOISTURE CORRECTION FACTOR FOR ELEVATED TEMPERATURE TESTS (SECTION 3.4.3.4.) FOR RAPESEED.

Temperature °C	A	B	C	D
20	6.00	0.0	6.00	46.40
40	6.30	0.18	6.12	47.33
60	7.18	0.35	6.83	52.82
70	7.90	0.45	7.45	57.62
80	8.44	0.58	7.86	60.79
90	8.99	0.87	8.12	62.80
100	9.70	0.99	8.81	68.68
110	10.32	1.11	9.21	71.23
120	10.92	1.16	9.76	75.48
130	11.34	1.22	10.12	78.28
140	11.93	1.32	10.61	82.06

A - Average weight of oil expressed from 30g of rapeseed from 3 tests (g).

B - Moisture Correction Factor (g)

C = A - B

$$D = \% \text{ oil expressed} = \frac{(A - B) \times 100}{0.437 \times 30g} \%$$

Experimental procedure as described in (a) for Cashew.

APPENDIX 2: SAMPLE CALCULATIONS FOR EXPERIMENTAL DATA (CHAPTER 3) AND THEORETICAL DATA (CHAPTER 6)

a) Pressure, Volume and Density at which oil expression commences. (Table 4, Fig. 17)

(i) Pressure: Applied load read from digital readout of Instron 1274 UTM.

eg. for Cashew: Load at which oil expression commenced: 2.9% of 500kN.

$$\therefore \text{Pressure} = \frac{2.9}{100} \times \frac{500\text{kN}}{\text{Area of cylinder.}}$$

$$= \frac{2.9 \times 500}{100 \times 44.18 \times 10^{-4}} \text{ kPa}$$

$$= 3.28 \text{ MPa.}$$

Five tests were done for rapeseed and cashew each.

(results in Table 4).

(ii) Volume

The reference point of the plunger was set as the top face of the cylinder (Fig.15) to give a full stroke of 92mm for each test. Pressing commenced at a constant actuator speed of 5mm/min until oil was until oil was observed to flow out of the pore pressure holes. Movement of actuator (plunger displacement) recorded on strip chart recorder. (Fig 17)

∴ From Fig. 17 for cashew:

Plunger displacement = 47mm.

Full stroke of plunger/cylinder rig.

(Fig 15) = 92 mm.

Height of oilseed cake at point of commencement of oil expression = 92 - 47 mm

= 45mm.

Volume of cashew cake = 45 X Area

$= 45 \times 4418.44 \times 10^{-4}$ ml

= 198.8 ml.

Five tests each done for rapeseed and cashew to give the average data in Table 4.

(iii) Density: For cashew:

Mass of oilseed in each case = 200g.

Volume from from (ii) above = 198.9 ml.

$$\text{Density} = \frac{200.0 \text{ g}}{198.9 \text{ ml.}} = 1005.5 \text{ kg/m}^3$$

(b) % Oil expressed: (Fig. Section 3.3)

Oil expressed collected in 25 ml graduated dcylinders. Volume read every 30s as explained in section 3.3.2.2.

For rapeseed:

Volume of oil expressed at t = 60s.

(Fig. 19) = 20 ml.

Volume of total oil present in 200g of rapeseed:

$$= \frac{\text{\% oil content X 200g}}{\text{density of rapeseed oil.}}$$

% oil content (Page 49) = 43.7%

density of rapeseed oil (Table 1) = 0.912 gl ml.

∴ Volume of total oil in 200g of rapeseed.

$$= \frac{0.437 \text{ X } 200}{0.192} \text{ ml}$$

$$= 94.8 \text{ ml.}$$

$$\text{\% oil expressed} = \frac{20 \text{ ml}}{94.8} = 21.1\% \text{ at t = 60s.}$$

which is plotted in Fig. 22 curve for 0.64% drainage area.

(c) Pore pressure measurement and calculation:

Details of Pressure Transducer used:

Manufacturers: Kulite Sensors Ltd.,
20, Wo St,
Basingstoke, Herts, England.

Type: Pressure Tranducer Model XTMS - 1 - 190 - 2000G. Sensitivity 0.03mV/6.895 KPa at 10 volts D.C.
Power input 10 volts D.C. Excitation.
Output mV - to - a recorder-

Recorder: Phillips multichannel recorder (12 channel). type 9404 372.00. 1.

Range	0 - 0.2 mV	FSD
	0 - 0.5 mV	FSD
	0 - 1.0 mV	FSD
	0 - 2.0 mV	FSD
	0 - 5.0 mV	FSD
	0 - 10.0mV	FSD
	0 - 2.0 mV	FSD
	0 -100.0mv	

For the drained tests where pressures were low the 0-1.0 mV FSD range used. For the undrained tests where pore pressures were high 0 - 100 mV used.

Three transducers used calibrated at 0.029, 0.03, 0.032 mV/6.895 kPa at 10V DC Excitation.

(d) Sample calculation for the theoretically calculated values of % oil expressed against time Fig. 40-48.

For Fig.40

From Table 18: For $t < t_o$

value of $K_1 = 0.376$, $K_2 = 0.126$

Theoretical Equation for $t < t_o$

$$Q_t = K_1(t+(1/K_2)(1-\exp(-K_2 t))) \text{ (ml)}$$

For t = 30s

$$Q_t = 0.376(30+(1/0.126)(1-\exp(-0.126 \times 30)))$$

$$= 14.2 \text{ ml.}$$

From 200g of rapeseed: Amount of oil present from Appendix 2 (b) = 94.8 ml.

∴ % oil expressed (Theoretical value)

$$= \frac{14.2}{94.8} \times 100 = 14.2\% \text{ (Plotted in Fig. 40)}$$

For $t > t_o$:

From Table 18: $K_3 = 71.2$, $K_4 = 0.0077$

Equation $Q_t = K_3 \ (1-\exp(-K_4 t))$

For $t = 600$:

$Q_t = 71.2(1-\exp(-600 X 0.0077)) = 70.5$ ml.

$= 70.5$ ml.

% oil expressed (Theoretical value) $= \frac{70.5}{94.8} X \ 100 = 75.2\%$

APPENDIX 3:

(a) Computer programme used to calculate values of K_1 K_2, K_3, K_4 in equations (43) and (46). (Computer IBM 360, APL - Iverson (1962)

Page - Programme - based on method of Himmelblau (1972)

Inputs:- (Page

Equations: $Q_t = K_1(1-\exp(-K_2 t))$

Data X - Time t(s)

Data Y - Volume of oil expressed Q_t (ml)

Approximate value of K_1, K_2 (X0).

Increment of iterations ΔX.

Output: (Page 264-262

Function value, (minimum value of the polyhedron (Error) K_1, and K_2.

```
        )10407:YLP
006) 14.36.39 09/01/78 CHEMENG403

 UCP\APL DAILY 10.00-12.00 AND 14.30-18.00

      )COPY  HPEVAPCOUCL
SAVED  16.10.54 08/31/78

      ∇FLEXI[⎕]
    ∇ FLEXI;X0;PAR;ALFA;BETA;GAMA;TEST;FLEX;R;XMAT;I;J
[1]    ⍝ FLEXIBLE POLYHEDRON SEARCH
[2]    ⍝ PAGE 148, APPLIED NONLINEAR PROGRAMMING, D.M. HIMMELBLAU
[3]    START 'FLEXI'
[4]    J←0
[5]    'DEFAULT PARAMETERS : ALPHA  = ';ALFA←1
[6]    '                     BETA   = ';BETA←0.5
[7]    '                     GAMMA  = ';GAMA←2.0
[8]    '                     ε      = ';TEST←0.0001
[9]    'DO YOU WANT TO MAKE ANY CHANGES? YES OR NO'
[10]   R←3⍴⍞
[11]   →(3>+/'YES'=R)/L001
[12]   'ENTER VECTOR OF VALUES : ALPHA, BETA, GAMMA AND ε'
[13]   R←⎕
[14]   ALFA←R[1]
[15]   BETA←R[2]
[16]   GAMA←R[3]
[17]   TEST←R[4]
[18] L001:'ENTER X0'
[19]   X0←,⎕
[20]   'ENTER AX[I]'
[21]   FLEX←⎕
[22]   'DO YOU WANT TO TRACE ITERATIONS? YES OR NO'
[23]   R←3⍴⍞
[24]   PAR←0
```

3

```
[25]  →(3>+/'XYZ'=N)/L002
[26]  PAR←1
[27] L002:N←ρX0
[28]  XMAT←((N+5),(N+1))ρX0,0
[29]  I←2
[30] L1:XMAT[I;I-1]←XMAT[I;I-1]+DELX
[31]  I←I+1
[32]  →(I≤N+1)/L1
[33] C1: I←1
[34] L2:XMAT[I;N+1]←F(,XMAT[I;⍳N])
[35]  I←I+1
[36]  →(I≤N+1)/L2
[37] L3:XMAT←XMAT[(⍋,XMAT[⍳N+1;N+1]),(N+1+⍳4);]
[38] S2:XMAT[N+2;⍳N]←(+/[1] XMAT[⍳N;⍳N])÷N
[39]  XMAT[N+2;N+1]←F(,XMAT[N+2;⍳N])
[40]  J←J+1
[41]  →(PAR=0)/L003
[42]  →(∨/(,XMAT[N+2;⍳N])≤0)/C9
[43]  →(XMAT[N+2;2]>0.01256)/C9
[44]  'F = ';PRINT FORM[1],(,XMAT[N+2;N+1]),FORM[2];' AT X = ';(,XMAT[N+2;⍳N])
[45] L003:XMAT[N+3;]←XMAT[N+2;]+ALFA×(XMAT[N+2;]-XMAT[N+1;])
[46]  XMAT[N+3;N+1]←F(,XMAT[N+3;⍳N])
[47]  →(XMAT[N+3;N+1]<XMAT[1;N+1])/S3
[48]  →(XMAT[N+3;N+1]>XMAT[N+1;N+1])/S6
[49]  →(XMAT[N+3;N+1]>XMAT[N;N+1])/S9
[50]  XMAT[N+1;]←XMAT[N+3;]
[51]  →C8
[52] S3:XMAT[N+4;]←XMAT[N+2;]+GAMA×(XMAT[N+3;]-XMAT[N+2;])
[53]  XMAT[N+4;N+1]←F(,XMAT[N+4;⍳N])
[54]  →(XMAT[N+4;N+1]≥XMAT[1;N+1])/C4
[55]  XMAT[N+1;]←XMAT[N+4;]
[56]  →C8
[57] C4:XMAT[N+1;]←XMAT[N+3;]
[58]  →C8
```

3

```
[59] S9:XMAT[N+1;ιN]←XMAT[N+2;ιN]
[60] S8:XMAT[N+5;]←XMAT[N+2;]+BETA×(XMAT[N+1;]-XMAT[N+2;])
[61]  XMAT[N+5;N+1]←F(,XMAT[N+5;ιN])
[62]  →(XMAT[N+5;N+1]<XMAT[N+1;N+1])/S7
[63] S10:XMAT←0.5×XMAT+(ρXMAT)ρXMAT[1;]
[64]  →S1
[65] S7:XMAT[N+1;]←XMAT[N+5;]
[66] S2:T←,XMAT[ιN+1;N+1]-XMAT[N+2;N+1]
[67]  T←((+/T×T)÷N+1)*0.5
[68]  →(T>EPST)/L3
[69]  ' '
[70]  'CONSTANT LOAD OIL EXPRESSION THEORETICAL EQUATION Y1 AND Y2 ARE CONSTANTS'
[71]  'IN EQN. OT=Y1[1-TWO THE POWER OF -Y2×T OBTAINED BY DARCYS LAW'
[72]  'OPTIMAL SOLUTION'
[73]  XMAT←XMAT[(⍋,XMAT[ιN+3;N+1]),(N+ 4 5);]
[74]  'FUNCTION VALUE = ';(,XMAT[1;N+1])
[75]  'AT X = ';(,XMAT[1;ιN])
[76]  '(';I;' ITERATIONS REQUIRED)'
[77]  [illegible]

[78]

      ∇I←F X
[1]   X[1]≥0
[2]   X[2]≥0
[3]   I←X[1]×1-*-X[2]×DATAX
[4]   I←+/(DATAY-I)*2
[5]   ∇


      DATAX←900  1050  1200  1350  1500  1650  1800  1950
      DATAY←68  70  71.5  72.5  74  74.5  75  76
      FLEXI

FLEXI       16:59:59        31/8/78

DEFAULT PARAMETERS : ALPHA = 1
                     BETA  = 0.5
                     GAMMA = 2.9
                     ε     = 0.0001
DO YOU WANT TO MAKE ANY CHANGES? YES OR NO
NO
```

```
ENTER X0
⎕:
      76.5  0.002543
ENTER AX[I]
⎕:
      .000005
0.0005
DO YOU WANT TO TRACE ITERATIONS? YES OR NO
YES
F =          8.14694 AT X = 76.50025    0.002543
F =          2.89669 AT X = 76.5001875   0.002418
F =          2.20860 AT X = 76.500125   0.002293
F =          2.20860 AT X = 76.500125   0.002293
F =          1.83405 AT X = 76.50023437  0.00232425
F =          1.84999 AT X = 76.50034375  0.0023555
F =          1.79562 AT X = 76.50022656  0.002339275
F =          1.83393 AT X = 76.50010937  0.00232425
F =          1.80262 AT X = 76.49998047  0.0023320625
F =          1.79490 AT X = 76.49985156  0.002339875
F =          1.79490 AT X = 76.49985156  0.002339875
F =          1.79490 AT X = 76.49985156  0.002339875
F =          1.79433 AT X = 76.49972705  0.0023338998437
F =          1.79326 AT X = 76.49912126  0.002337970703
F =          1.79137 AT X = 76.49792077  0.002337089355
F =          1.78996 AT X = 76.49652027  0.002336208008
F =          1.78413 AT X = 76.49368541  0.002337365479
F =          1.77423 AT X = 76.48861372  0.002341431528
F =          1.75750 AT X = 76.47557451  0.002348651136
F =          1.75036 AT X = 76.46253531  0.002355870643
F =          1.73297 AT X = 76.45125264  0.002358277175
F =          1.68727 AT X = 76.43092015  0.002358397584
F =          1.60282 AT X = 76.37888455  0.002365490913
F =          1.46746 AT X = 76.2704865   0.0023725727852
```

```
F =    1.40932 AT X = 76.01660512   0.002399802974
F =    1.34612 AT X = 76.00327657   0.002412937236
F =    1.31225 AT X = 75.98514202   0.002424191798
F =    1.30627 AT X = 75.96941947   0.002436348961
F =    1.31250 AT X = 75.93365947   0.002435832586
F =    1.31642 AT X = 76.0555923   0.0024190013497
F =    1.30521 AT X = 75.98202268   0.002431984651
F =    1.30962 AT X = 75.93104653   0.002440050814
F =    1.30607 AT X = 75.96087651   0.002436900596
F =    1.30630 AT X = 75.98180169   0.002434226981
F =    1.30573 AT X = 75.97211799   0.002425133685
F =    1.30525 AT X = 75.97523359   0.002433413265
F =    1.30521 AT X = 75.97834918   0.002431692845
F =    1.30522 AT X = 75.97359156   0.002433209836
F =    1.30519 AT X = 75.98200162   0.002431618741

CONSTANT LOAD OIL EXPRESSION THEORETICAL EQUATION X1 AND X2 ARE CONSTANTS
IN EQN. QT=X1[1-EXP TO THE POWER OF -X2*T OBTAINED BY DARCYS LAW
OPTIMAL SOLUTION
FUNCTION VALUE = 1.305189419
AT X = 75.98200162  0.002431618741
(39 ITERATIONS REQUIRED)

TIME :   53.43 SECONDS
```

TABLE 17: THEORETICALLY CALCULATED VALUES OF % OIL EXPRESSED FOR CASHEW USING EQUATION 43 & 46

cf. Experimental results in Table. 7.

R →		377.2 k Pa/s					188.4 k Pa/s					94.3 k Pa/s					62.8 k Pa/s				
A ↓ % / t → (s)	Equation	60	150	240	600	1800	60	120	300	900	1800	60	120	300	600	1800	60	300	900	1200	1800
0.64%	43	30.2	68.5				15.6	29.3	67.7			10.7	19.0	42.9	75.9		3.7	28.7	80.2		
	46		56.4	65.8	72.2	72.3			64.9	79.2	79.7				70.9	79.4			74.6	79.4	82.8
1.85%	43	22.4	51.6				11.7	21.0	48.9			8.4	14.8	33.9	65.6		6.2	24.2	68.6		
	46		47.1	56.5	63.9	64.3			47.5	63.4	66.3				55.9	64.1			56.3	60.7	64.1
3.60%	43	9.9	23.4				8.5	15.4	36.3			5.4	9.6	21.9	42.4		4.2	16.6	47.3		
	46		18.5	26.8	33.7	38.8			23.3	30.4	34.3				31.2	36.9			28.3	30.9	33.1
5.70%	43	7.7	18.3				7.1	12.9	30.3			4.2	7.5	17.3	33.6		3.5	14.1	40.2		
	46		16.9	20.7	30.3	33.1			19.9	30.8	33.1				26.5	32.8			25.2	27.6	29.7
8.30%	43	6.8	16.3				4.1	7.5	17.7			3.4	6.0	14.1	27.5		2.7	10.8	31.1		
	46		12.3	18.4	27.6	30.7			16.6	27.2	29.6				21.4	28.1			22.0	24.5	27.1
			t_o						t_o						t_o				t_o		

APPENDIX 4: APPLICATION OF MATHEMATICAL MODEL TO A HYDRAULIC PRESS.

(a) Computation of K_3, K_4: from laboratory data:

From equation

Given:

t	300	600	900	1800s
Qt	46	56	58	64 ml.

$$Qt = K_3(1-e^{-K_4 t})$$

Substitute values of Qt, and t at t = 300s, 600s and solve for K_4:

(A) $$46 = K_3(1-e^{-300K_4})$$

(B) $$56 = K_3(1-e^{-600K_4})$$

But $(1-e^{-600K_4}) = (1-e^{-300K_4})(1+e^{-300K_4})$

Therefore, $56 = K_3(1-e^{-300K_4})(1+e^{-300K_4})$

Dividing (A) and (B)

$$\frac{46}{56} = \frac{1}{(1+e^{-300K_4})}$$

$$\therefore \quad 1 + e^{-300K_4} = \frac{56}{46}$$

$$-300K_4 = \ln(0.217)$$
$$= -1.53$$

$K'_4 = 0.0052.$

Doing the same when t = 900, and t = 1800s.

$$(1 + e^{-900K_4}) = \frac{64}{58}$$

$$\therefore \; -900K_4 = -2.3$$

$$K_4 = 0.0026$$

Taking the average of the 2 values of K_4

$$K_4 = 0.0044$$

This is fairly near the 0.0055 which was calculated by computer for values from 150s to 1920s.

From this value of K_4, the value of M can be calculated, and by taking $K_3 \doteq$ the value of Q_f after large $t \to 1800s$, value of k - the coefficient of permeability of the cake can be calculated.

The values of k'_3 and K'_4 for the press can then be calculated as done in (b).

(b) Calculation of K_3 and K_4 for the expeller:

Volume of cake = $90 \times 36 \times 5\ cm^3$

$= 16200 \times 10^{-6}\ m^3$

Area of press = $3240 \times 10^{-4}\ m^2$

Density of rapeseed when oil expression commences

$= 993\ Kg/m^3$

Mass of rapeseed charged into 1 press box:

$= 993 \times 16200 \times 10^{-6}$ Kg

$= 16086.6 \times 10^{-3}$ Kg

Volume of oil present in this mass

$$= \frac{43}{914} \times \frac{1}{100} \times 16086.6 \times 10^{-3}$$

$= 7568 \times 10^{-6}\ m^3$

From experementiol data $K_4 = 0.0044$ H = 6.0 cm

$$K = \frac{\pi^2 M}{4H} \rightarrow \text{Equation (48)}$$

$$M = \frac{4H\ K}{\pi^2} = 0.063 \times 10^{-4}\ m/s$$

From experiment.al data when t→large, $Q_t = K_3$ and by equation (47)

$$K_3 = \frac{64H^3 RA\ K}{\pi^4 M^2 \rho g} \left\{ \exp\left(\frac{\pi^2 M t_o}{4H^2} - 1 \right) \right\}$$

Darcy's coefficient of permebiality: k

$$k = \frac{\pi^4 M^2 \rho g K_3}{64H^3 RA_c \left\{ \exp\left(\frac{\pi^2 M t_o}{4H^2} \right) - 1 \right\}},$$

Laboratory details:

$R = 377.2 \times 10^{3}\ N/m^2 s.$ $\rho g = 993 \times 9.81\ N/m^3$

$M = 6.3 \times 10^{-6}\ m^2/s$ $K_3 = 64 \times 10^{-6}$

$A_c = 44.2 \times 10^{-4}\ m^2$ $t_o = 150\,s$ $H = 60 \times 10^{-2}\ m$

Coefficient of permeability

$$K = \frac{\pi^4 \times 6.3^2 \times 10^{-12} \times 993 \times 9.81 \times 64 \times 10^{-16}}{64 \times 6.0^3 \times 377.2 \times 10^{-3} \times 0.93 \times 44.2 \times 10^{-4}}$$

$$= \frac{24354.6 \times 993 \times 716 \times 10^{-18}}{13824 \times 352.6 \times 10^{-3} \times 44.2 \times 10^{-4}}\ m/s$$

$$= 80.5 \times 10^{-11}\ m/s$$

For the press box:

$A = 3240 \times 10^{-4}\ m^2$ $H_p = 5.1 \times 10^{-2}\ m$

$R = 76.6 \times 10^{3}\ N/m\ s$ $M = 6.3 \times 10^{-6}$

$t_o = 360s$ $k = 80.5 \times 10^{-11}\ m/s$

$$K_{4(press)} = \frac{\pi^2 M}{4H_p^2} = \frac{\pi^2 \times 6.3}{4 \times 5.1^2} \times \frac{10^{-6}}{10^{-4}} = 6.1 \times 10^{-3}\ 1/s$$

$$K_{3(press)} = \frac{64 \times 5.1^3 \times 10^{-6} \times 10^3 \times 3240 \times 80.5 \times 10^{-11} \times 8.0}{4 \times 6.3^2 \times 10^{-12} \times 993 \times 9.81}$$

$$= \frac{8489.7 \times 49330.4 \times 3240}{3865.8 \times 9741} \frac{\times 10^{-19}}{\times 10^{-12}}$$

$$= 36033.4 \times 10^{-7}\ m^3$$

$$= 3603.34 \times 10^{-6}\ m^3$$

(c) Application of Equation (46) for oil expression in hydraulic expellor.

Equation for 1 press box in a hydraulic expeller at room temperature for rapeseed is:

$$\% \; Q_t = \left\{ \frac{3603}{7568} \left\{ 1 - \exp - \left(0.0044t\right) \right\} \right\}$$

and values of oil expressed (%) at times required are:

t (min)	6	10	15	20	25	30
Q_t (%)	37.8	44.2	46.7	47.4	47.5	47.6

In data from hydraulic press mills for cottenseed at temperature 195°F, Carter (1953) gives the following results of residual oil in the cake : after pressing for time t;

t (mins)	6	10	20	30	60	90
Q (Residual oil in cake %)	10	9.0	8.0	7.5	7.0	6.5

Converting the above values to % oil expressed:

Cottonseed: Oil Content = 19% by weight

If x% is the oil expressed and y% is %oil in the oilseed cake after expression, then the following relationship holds for cottonseed with 19% initial oil content:

$$\frac{y}{100} = \frac{19-x}{100-x}$$

$$\therefore \quad x = \frac{1900-100y}{100-y}$$

$$\% \text{ oil expressed} : = \frac{x}{19} \times 100\%$$

Hence converting the data of residual oil to % oil expressed we get:

t (min)	6	10	20	30	60	90
Q_t (% oil expressed)	52.6	57.8	62.9	65.4	67.9	70.3

These values are for oil expressed from cottonseed at 90°C. Converting the % oil expressed from rapeseed at room temperature to 90°C - (from fig. 11-page 59 if the rapeseed is heated to 90°C the % oil expressed increases by 30%. Hence at 90°C, 130% of the oil expressed at room temperature is expressed.

∴ For rapeseed:

t (mins)	6	10	15	20	25	30	60	90
Q_t (90°C) %	49	58	61	62	62.1	62.2	62.3	62.4%

These values are plotted in Fig. 5 Chapter 7.

APPENDIX 5: APPLICATION OF MATHEMATICAL MODEL TO SCREW PRESS

(a) Calculation of Residence time:

Feed rate = 59091kg/24 hours.

= 0.68 kg/s.

Volume of oilseed (rapeseed) the expeller can take

Assume an average gap of 1" = 2.5 cm. = H

Volume = $\pi D \times L \times H$

$$D = \frac{22.5 + 20.0}{2} = \frac{42.50 \text{ cm}}{2} = 21.25$$

L = Length of cage = 310 cm.

$$\therefore \quad \text{Volume} = \pi \times 21.25 \times 310 \times 2.54 \times 10^{-6} \text{ m}^3.$$

$$= 52572.7 \times 10^{-6} \text{ m}^3.$$

Mass of oilseeds the expeller can take = Density of oilseeds X Volume of cage

$$= 993 \text{ kg/m}^3 \times 52572.7 \times 10^{-6} \text{ m}^3.$$

$$= 52204.7 \times 10^{-3} \text{ kg}.$$

$$= 52.2 \text{ kg}.$$

Feed rate = 0.68 kg/s

$$1\ kg = \frac{1}{0.68}\ \frac{s}{kg}$$

$$52.2\ kg = \frac{1}{0.68} \times 52.2 = 76.8s = 77s$$

$\therefore$ the residence time = 77 seconds. For the feedrate of 65 short tons /24 hrs.

(b) Calculation of M and k for rapeseed from laboratory data.

Because of the complexity of equation (43) for an increasing applied load it is not possible to find a method for approximating values of the constants K_1 and K_2 as was done for the hydraulic expeller data in Appendix 4.

Therefore, equation 46 has to be solved by aid of computer using the data obtained from the laboratory tests for K_1 and K_2.

Use the data for drainage area of 1.85% as this is nearest to drainage areas common in expellers.

Value of K_1 and K_2 computed (Table 15)

$$K_1 = 0.289\ \frac{ml}{s} \qquad K_2 = 0.148\ {}^{=1}/s.$$

$$K_2 = \frac{\pi^2 M}{4H^2} \qquad H = 6.0 \text{ cm.}$$

$$\therefore \quad M = \frac{4H^2K}{} = 4 \times 0.148 \times 4 \times 6^2 \times 10^{-4}$$

$$= 2.13 \times 10^{-4} \ \frac{m^2}{s}$$

---

and

$$M = 2.13 \times 10^{-4} m^2/s$$

$$K_1 = \frac{16HA_cRk}{\pi^2 M\rho g} = 0.289 \frac{ml}{s} \qquad A_c = 44.15 \times 10^{-4} m$$

$$R = 377.2 \times 10^3 \text{ N/m s}$$

$$\rho g = 993 \times 8.81 \text{ N/m}$$

$$K_1 = \frac{M\rho gK}{16HA\,R} = \frac{\pi^2 \times 2.13 \times 10^{-4} \times 993 \times 9.81 \times 0.289 \times 10^{-6}}{16 \times 6.0 \times 10^{-2} \times 44.18 \times 10^{-4} \times 377.2 \times 10^3}$$

$$= 0.00375 \times 10^{-5} m/s \qquad = 3.75 \times 10^{-7} m/s$$

(c) Calculation of K_1 and K_2 for screw expeller:

H for the expeller = 2.54 cm for the thickness of the cake + 0.62cm for ½ the width of the drainage bars

R - assume a linearly increasing load from the feed end of shaft to discharge end with a maximum load of 232 MPa.

$$\therefore \quad R = \frac{232 \text{ MPa}}{\text{Residence time}} = 3.0 \text{ MPa/s.}$$

Drainage Area A = ½ the circumference X length

$$= \frac{\pi D}{2} \times L \quad = \frac{\pi \times 21.25 \times 310}{2}$$

$$= 10349 \times 10^{-4} \text{ m} .$$

Sp Gravity for rapeseed oil = ρg = 993 X 9.81 N/m^3.

M for rapeseed = 2.13×10^{-4} m /s (see(b) above)

k for rapeseed = 3.75×10^{-7} m/s (see(b) above)

$$\therefore \quad K_2 = \frac{\pi^2 M}{4H^2} = \frac{\pi^2 \times 2.13 \times 10^{-4}}{4 \times 3.2^2 \times 10^{-4}} = 0.51 \text{ 1/s}$$

$$K_1 = \frac{16HA_cRk}{M\rho g} = \frac{16 \times 3.2 \times 10^{-2} \times 10349 \times 10^{-4} \times 3 \times 10^{+6} \times 3.75 \times 10^{-7}}{\pi^2 \times 2.13 \times 10^{-2} \times 993 \times 9.81}$$

$$= 29.2 \times 10^{-5} \frac{m^3}{s}$$

$\therefore$ Values of K_1 and K_2 for the expeller are 0.51 1/s and 29.2×10^{-5} m^3/s.

(d) Calculation of oil expressed for the Dammon Croes Expeller:

Therefore the equation for the volume of oil expressed from oilseed in the expeller from t=o, to t=t is:

$$Q_t = 29.5 \times 10^{-5} \left(t + \left(\frac{1}{0.51}\right) (1 - \exp(-0.51t)\right)$$

Volume of oil present in fed rapeseed:

$$= \frac{0.43 \times 52.2 \text{ kg}}{912 \text{ kg/m}^3} = 24.6 \times 10^{-3} \text{ m}^3$$

Therefore % oil expressed:

$$Q_t\,\% = \frac{29.5 \times 10^{-5}}{24.6 \times 10^{-3}} \left\{ t + \left\{\frac{1}{0.51}\right\} \left\{1 - \exp(-0.51t)\right\}\right\} \times 100$$

$$= 1.2 \times \left\{ t + \left\{\frac{1}{0.51}\right\} \left\{1 - \exp(-0.51t)\right\}\right\}$$

The above equation can be used to calculate the % of oil expressed along the expeller from t = 0, to when the oilseed cake is discharged from the expeller

i.e. t = 77s

t (s)	0	10	20	30	40	50	60	70	77
Q_t (%)	0	14.3	26.4	38.3	50.4	62.4	74.4	86.3	95.0

TABLE I

Descriptions of Screw Presses

Company	Model	Wt (tons)[a]	Capacity (tons)	Drive (HP)	Cage diameter (in.)	Cage length (in.)	Wt:Capacity (ton:ton)	Capacity:Cage length (ton:in.)	Capacity:HP (ton:HP)
Anderson IBEC	Red Lion	4	5	20	-	33	1:1.25	1:6.6	1:4.00
	Model 33	10	40	80	-	58.625	1:4.00	1:1.47	1:2.00
	Model 55	11.5	50	125	-	83.625	1:4.35	1:1.61	1:2.50
	11-66	-	200	-	12	66	-	1:0.33	-
Dammon-Croes	SP 50	18.7	65	140	8.86 x 7.87	122	1:3.48	1:1.87	1:2.15
	SP 125	20	160	140	9.84 x 8.66	122	1:8.00	1:0.76	1:0.87
French Oil Mill	F44	9.5	22	75	7	44	1:2.31	1:2.00	1:3.41
	F44 with 2x11 in. extension	11	42	125	7	66	1:3.00	1:1.57	1:2.98
	F66	10.5	36	125	7	66	1:3.42	1:1.83	1:3.47
	F77	12	42	125	7	77	1:3.50	1:1.83	1:2.98
	F88	13.5	42	125	7	88	1:3.11	1:2.09	1:2.98
	D66	13	42	200	7	66	1:3.23	1:1.57	1:4.76
	D77	15	50	200	7	77	1:3.33	1:1.54	1:4.00
	D88	17	65	200	7	88	1:3.82	1:1.35	1:3.08
	C3300	21	110	300	10½	102	1:5.24	1:0.93	1:2.72
	B1500	15	100	100	8¾ x 7	55	1:6.67	1:0.55	1:1
	B2100	18	170	200	12 x 10½	55	1:9.44	1:0.32	1:1.18
	B2 6600	21.25	460	600	16 x 14	99	1:21.65	1:0.24	1:1.3
Krupp Maschinen	L.P.	11.5	46	125	7.874	59.055	1:4.00	1:1.28	1:2.72
	S.V.P.	10.25	190	180	12.598 x 10.24	76.063	1:18.54	1:0.40	1:0.95
Simon-Rosedowns	Mk 2A	7.7	20	50	6	66	1:2.59	1:3.30	1:2.50
	Mk 3A	8.4	33	75	6	88	1:3.93	1:2.67	1:2.27
	"E" type	13.4	80	200	7	103	1:5.97	1:1.29	1:2.50
	"G" type	13.1	190	240	9.84 x 8.98	109.84	1:14.5	1:0.57	1:1.26
Speichim	301	7	22	40	8.66	55.12	1:3.14	1:2.51	1:1.82
	400	12	38.5	75	9.45	72.83	1:3.21	1:1.89	1:1.95
	500	17.5	143	125	11.02	88.58	1:8.17	1:0.62	1:0.87
	500L	21	175	150	11.02	110.23	1:8.33	1:0.63	1:0.86
Stork-Amsterdam	R400	4.25	45	40	-	-	1:10.59	-	1:0.89

[a]In all cases, short tons.

REFERENCES:

Aboaba, F.O; Bruhn H.D; Livermore D.F; 1970
Processing characteristics of macrophytes as related to mechanical harvesting.
Trans A.S.A.E. 14 (16) 1004 - 1008.

Aboaba, F.O; Bruhn, H.D; Koegel R.G; Livermore D.F;1973
Some fundamental principles of dewatering aquatic vegetation.
Trans A.S.A.E. 16; 430-433.

Aboshi, H; Yoshikuni, H; and Maruyama S. 1976
Constant loading rate consolidation test.
Soils and Foundations 10, (1) 44-56

Appelquist L.A. Ohlson R; 1972.
Rapeseed.
Elsevier Publishers, Amsterdam.

AOAC 1975
Association of official and agricultural chemists,official methods of analysis.
Editor W. Horwitz 12th Edition 1975.

Battino,R; Clever L.H; 1966
'The solubility of gases in liquids'
Chemical Review 66 (4): 395-463.

Barden, L; Madedor, A.O; Sides, G.R; 1972
The flow of air and water in partly saturated clay soil.
In 'Fundamentals of Transport Phenomena in Porous Media'.
I.A.H.R.- Elsevier, Amsterdam.

Baskerville, W.H; Wamble A.C. 1947.
Determination of economically optimum processing times for hydraulic extraction of cottonseed oil.
The University of Tennesee Engineering Experiment Station Bulletin no. 13.

Bernadini, E; 1976
Batch and continuous solvent extraction
J.Am. Oil Chemists Soc. 53 (6) 275 - 278.

Boiko, A.Ya 1975
Intensification of the mechanical dewatering of the green mass.
Agricultural Engineering Abstracts no. 1337:Vol 3 (5).

Bishop, A.W; Blight, G.E; 1963
Some aspects of effective stress in partly saturated soils.
Geotechnique 13 (3) 177-197.

Biot, M.A. 1941
General theory of three dimensional consolidation.
J. of Appl. Physics 12: 155- 164.

Boucher, D.F; Brier J.C. Osburn J.O 1942.
Theory of solvent extraction of oil from oilseeds
Trans. Am. Inst. Chem. Engrs. 38, 967-993.

Brian R. 1976
Texturized protein products
Proc. of World Conf on Oilseeds and Veg. Oil.
Processing Techn. March 1-5, 1976 Amsterdam.

British Standards B.S; 631: 1967.
Specification for crude rapeseed oil.

British standards, B.S; 1377:1975.
Methods of test for soils for civil engineering purposes.

Burgess, J; 1971
Observation on structure and differentiation in plasmodesmata
Protoplasma 73: 83 - 95

Carter, C.L 1953.
An investigation of some factors affecting the efficiency of hydraulic pressing of cottonseed.
Uni. of Tenn. Eng. Exp. Sta. Bulletin no. 18.

Carr, D.J; 1976
Plasmodesmata in growth and development
In'Inter-cellular Communication in Plants'
Edited by Gunning and Robards 1976.

Considine, J.A; and Kriedman P.E; 1972
Fruit splitting in grapes: Determination of critical turgor pressure.
Australian Journal of Agricultural Research 23: 17 - 24.

Diekert J.W; Diekert M.C; 1972.
The deposition of vacuolar proteins in oilseeds
In'Symposium Seed Proteins' Edited by G.E. Inglett.
A.V.IPublishing Company Westput, Connecticut.

Diekert,J.W; Diekert, M.C; 1976

The chemistry and cell biology of the vacuolar proteins of seeds.

J. of F d. Sc. 41 (3) 475-482.

Dunning J.W. 1976

Unit operations in a mechanical oil extraction mill.

J. of Am. Oil Chem. Soc. 1956 128 - 131.

French, A.W; 1956

Fundamentals of screw press operations and a discussion in new developments in screw presses

Oil Mill Gazetteer March 1956 18-21

Frolich, P.K; Tauch, E.J; Hogan J.J; Peer, A.A; 1931

Solubilities of gases in liquids at high pressures

Ind. and Eng. Chem. 23 (5) 548 - 550.

Garcia,E.J; 1976.

Processing peanuts and cottonseed.

J. Am. Oil Chemists Soc. 53 (6) 259-260.

Gunning, G.E.S; Robards A.W; 1976

Inter-cellular communication in plants: Studies on plasmodesmata

Springer Verlag Berlin.

Gurnham, C.F; Masson,H.J; 1946.

Expression of fluids from fibrous material

Ind. Eng. Chem. 33 (12) 1309-1312

Gustafson, R.J; Segerlind L.J; 1977

'Continuum theory for gas-solid-liquid media 1-Theory development'

Trans. A.S.A.E. 20 (6) 1186-1189

Gustafson, R.J; Segerlin L.J- 1977
'Continuum theory for gas-solid-liquid media
11- Modelling by use of finite element method.'
Trans. A.S.A.E. 1190 - 1200

Gustafson,R.J; 1979
Personal Communication
Department of Agricultural Engineering
University of Minesota.
St. Paul, Minnesota 55108.

Hensarling, T.P; Yatsu L.Y; Jacks T.J; 1970
Extraction of lipids from cottonseed tissue
11. Ultra-structural effects of lipid extra-
ction
J. Am. Oil Chem. Society 47:224 - 225.

Heyenga,J; Personal communication.
Electron Microscope Unit.
I.I.R.S. Dublin.

Hough,B.K; 1975
Basic soils engineering.
The Reinhold Press Company New York.

Himmelblau, D.M; 1972
Applied non-linear programming.
McGraw Hill Book Company New York.

Hickox,G.H; 1953.
Some factors affecting hydraulic extraction
of cottonseed oil
J. Am. Oil Chem. Society 30 481 - 486.

Holdren,R.D; Harris N.L; Buckhardt G.J; 1972
Squeezing juices from forages
Trans of A.S.A.E. 15 (6) 1044 - 48.

Hussey,1979.
Personal communication.
Department of Industrial Microbiology
University College Dublin.

Iverson,K.E; 1962
A programming language.
John Wiley and Sons London.

John,D; 1978.
Personal communication
Electron microscope unit.
Department of Botany
Trinity College
University of Dublin.

Jennings, J.E.B; and Burland,J.B; 1962
Limitations to the use of effective stresses
in partially saturated soils.
Geotechnique 18:432-448.

Koegel, R.G; Bruhn H.D; 1972
Pressure fractionation characteristics of
alfalfa
Trans A.S.A.E 15 (5) 856-860

Koegel, R.G; Fomin, V.I; Bruhn 1973a
Roller maceration and fractionation of
forages.
Trans. A.S.A.E. 1973 236 - 240

Koegel, R.G; Fomin,V.I; Bruhn, H.D; 1973b
Cell rupture properties of alfalfa
Trans A.S.A.E. 16 (4) 712-716.

Koegel, R.G. 1974
Harvesting and processing equipment for alfalfa plant juice protein concentrates
Proc. 4th annual alfalfa symposium
Madison Wisconsin.

Koehler, J.K- 1973
Advanced Techniques in biological electron microscopy
Springer Verlag. New York.

Koo,E.C; 1942
Expression of vegetable oils: A general equation on oil expression.
Ind. Eng. Chem. 34: 342-345

Kwaitkowsaka,M; Maszewski, J; 1976
Plasmodesmata between synchroniously and unsynchroniously developing cells of anthredial filaments of chara vulgris L.
Protoplasma 87: 317-327.

Lambe, T.W; and Whitman,R.V; 1969
Soil mechanics.
J.Wiley & Sons. New York.

Maekawa, T; Yoshizake, S; Yamazawa, S; Usui, N; 1977
A basic experiment on the disintegration of single cells.
J. of Soc. of Agric. Machinery, Japan 39 (1) 31 - 33.

Markham, A.E; and Kobe, K.A; 1941.
The solubility of gases in liquids.
Chem. Rev. 28 (3) 519 - 588.

Matyas, E.L; Radhakrisham H.S; 1968.
Volume change characteristics of partially saturated soils.
Geotechnique 12 (2) 125-144.

Mears, P- 1976
Membrane separation process.
Elsevier Publishing Co. Amsterdam.

Mielke, S; 1976.
World supply and demand situation for oilseeds oils and meats.
Proc. World. Conf. on Oilseeds and Veg. oil Proc. Techn. Amsterdam March 1-5, 1976.

Mohapatra, A.R; Bhat, N.J- Murthy, K.N; 1972.
Note on the protein content of some varieties.

Mohsemn, N.N; 1970
Physical properties of plant and annual material Vol. 1.
Gordon Beach Publications, New York.

Murti, K.S; and Achaya, K.T; 1974
Cottonseed- Chemistry and Technology
C.S.I.R. India. New Delhi.

Myers, G.E; 1971
Analytical methods in conduction heat transfer
McGraw Hill Co. New York.

Norris, F.A; 1964

Extraction of fats and oils

In 'Bailey's Industrial Oil and Fat Products'

Edited by D.Swern

Interscience Publishers London.

O'Farrell, N; 1976

Oilseed rape

Farm bulletin

Department of Agriculture and Fisheries.

Dublin. Jan. 1976.

Osburn, J.O; Katz, D.L- 1944

Theory of solvent extraction

Trans. Am. Inst. Chem. Engrs. 40 511-531

Othmer, D.F; Aggarwal, J.C; 1955

Chemical Engineering progress.

51 372 - 378.

Robards, A.W; 1968

A new interpretation of plasmodesmata ultra-structure.

Planta 82: 200-210

Robards, A.W; 1970

Electron microscopy and plant ultrastructure.

McGraw Hill Co. New York.

Robards, A.W; Jackson, S.M; Clarkson, D.T; Sanderson, J; 1973

The structure of Barley roots in relation to the transport of ions into the stele.

Protoplasma 77: 291-311.

Robards, A.W; 1975.

Plasmodesmata

A.Rev.Physiol. 26 13-29.

Robards A.W; Clarkson, D.T; 1976)

In intercullar communication in plants.

Studies in plasmodesmata

Edited by Gunning and Robards. Springer Verlag.Berlin.

Robards, A.W; 1978

Personal communication.

Department of Biology.

University of York, Heslington, York, England.

Roath, S; Newell, D; Polliack, A; Alexander E; Lin, P.S; 1978

Scanning electron microscopy and the surface morphilogy of human lyonphocytes.

Nature 273: 15-18. (May 4, 1978).

Russell, D.C; 1969

Cashew nut processing F.A.O

Agric. Sciences Bulletin note. Rome.

Scott, C.R; 1974

An introduction to soil mechanics and foundations 2nd Edition

Applied Science Publishers Essex, England.

Schiffman, R.L; 1958

Consolidation of soil under time dependent loading

Proc. of High Res. Board (USA) 1958 584-616

Scheidegger, A.E; 1961

The physics of flow.through porous media

University of Toronto Press.

Smith,A; and Circle, J.C; 1972.

Soyabeans, Chemistry and Technology

A.V.I. Publishers Westport, Connecticut.

Stein, W; Glaser, F.W; 1976.

Continuous solvent extraction of sunflower seed, Groundnuts plam kernels, rapeseed and copra.

J.Am. Oil Chemists Soc. 53 (6) 283-285.

Stirling, J; Personal communication

Biological Sciences

Electron Microscope unit

University College, Dublin. 4.

Swartzberg,H.G; Rosenau, J.R; Richardson, G; 1971

The removal of water by expression.

A.I.C.H.E. symposium series. no. 163. Vol. 73

Water Removal Processes.

Swern, D; 1964

'Baileys Industrial Oil and Fat Products.'

Interscience Publishers London.

Taylor, D.W; 1966

Fundamentals of soil mechanics.

J.Wiley and Sons New York.

Terzaghi, K; 1943

Theoretical soil mechanics.

J.Wiley and Sons New York.

Tindale, L.H; Hill- Haas, S.R; 1976

Current equipment for mechanical oil extraction.

J.Am. Oil. Chem. Soc. 53 (6) 264 - 266

Tyree, M.T; 1970

The symplast concept - A general theory of symplastic transport according to the thermodynamics of Irreversible Process.

J. of Theor. Biology (20) 181-214.

Vaughn, J.F; 1970

Structure and utilization of oilseeds.
Chapman and Hall Ltd.,, London.

Vix, H.L.E; Gardner, H. K, Lambou, M.G Rollins M.L 1972

Ultrastructure related to cottonseed and peanut processing and products
In Symposium Seed Proteins
Edited by Inglett G.E; A.V.I. Publishing Co. Westport, Connecticut.

Ward, J; 1976.

Processing of high oil content seeds in a continuous screw press.
Proc. of World Conf. on Oilseeds and Veg.oil Processing
Technology;Amsterdam, March 1-5, 1976.

Wilun, Z; Starzewski, K; 1972

Soil mechanics and foundation engineering Vol. 1
Intertext Brooks, London.

Weast, C; Handbook of Physics and chemistry.

Edited by Weast C.McGraw Hill Bk Company New York.

Woodroof, J.G; 1969

Tree nuts - Production, Processing and Products.
Vol. 1.
A.V.I. Publishing Company, Westport, Connecticut.

Woolrich, W.R; Carpenter. E.L- 1935

Mechanical processing of cottonseed.
Engineering Expt. Bulletin Station,
University of Tennessee, Knoxville. USA.

Wylie, C.R; 1966

Advanced Engineering Mathematics

3rd edition McGraw Hill Book Company. New York.