

Cranfield University

Silsoe

EngD Thesis

P.R. Hunt

**Physical Preparation of Rapeseed for
Mechanical Extraction of Oil**

Supervisor: Dr. B. Clarke

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ABSTRACT

The study investigated the preparation treatment of rapeseed for the mechanical extraction of oil. Current mechanical oil extraction processes achieve an extraction efficiency of approximately 85% resulting in a residual oil in the press cake following high pressure pressing of 8 to 10%. The aim was to enhance the extraction efficiency of the process to leave approximately 3% residual oil in the press cake (as specified by the sponsor) by improving the preparation of rapeseed. Enhancing the extraction efficiency of the mechanical extraction process to achieve a residual oil content of 3% will provide a commercially viable alternative to solvent extraction omitting the use of hazardous chemicals from the oil extraction process.

A practical programme of work was carried out to investigate the potential of introducing extrusion technology as a replacement preparation treatment to flaking and conditioning currently used in the mechanical extraction process. The experiments were in two major stages. Initial trials were carried out using a laboratory scale Brabender single screw extruder and the second set, with a larger scale Almex single screw extruder.

The findings from the investigation indicated that, at the optimum operating conditions, the Brabender extruder was effective in breaking virtually every seed with a high level of cell damage apparent from the analysis of the rapeseed microstructures. The residual oil in cake following extrusion and pressing in a hydraulic ram press was 9.37% and the milling defect, a commercially used indicator of seed preparation efficiency, as low as 0.7.

The analysis of the results from the larger scale extrusion experiments revealed that the performance of the extrusion process as a preparation treatment reduced with a scaling up in size of operation. The laboratory scaled extrusion trials revealed a greater percentage of cell structure damage, lower milling defect values and a 26% greater process extraction efficiency, at process optimums, than the larger scale trials.

With current extrusion technology the introduction of extrusion to a commercial scale processing plant will not improve the oil yield of the process sufficiently to make the mechanical extraction process commercially competitively against a current solvent extraction plant. The process will only become a viable alternative to solvent extraction if future advancements in large scale extruder design can achieve the preparation efficiency attainable with laboratory scale extrusion.

A commercial scale plant with an extrusion preparation treatment, achieving a preparation performance equivalent to that of the small scale Brabender, will increase the extraction efficiency of the process. The increase in extraction efficiency, together with the elimination of the steam requirement from the process, achieved from the elimination of conditioning from the preparation process, will increase the profitability of the mechanical extraction process nearing that of a solvent extraction plant. The net profit would increase from £6.33/t for current mechanical extraction to £10.03/t with the introduction of extrusion, this is still less than £11.19/t achievable with solvent extraction.

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1. INTRODUCTION

1.1 Importance of the investigation

Oilseed rape is of significant importance to UK agriculture and is currently the third most prevalent crop grown in the UK behind wheat and barley. In 1998 531,000 ha, representing over 10% of UK cropped farmland, of oilseed rape was grown in the UK (MAFF, 4th February 1999).

Oilseed rape is also of major importance to the UK vegetable oil industry. In 1998 1,621,300 tonnes of oilseed rape was processed in the UK producing 669,400 tonnes of crude rape oil. This figure represents 73% of the total crude vegetable oil produced in the UK during 1998 (MAFF, 28th May 1998, 29th August 1998, 13th November 1998 and 23rd February 1999).

The current and most economic processing technique used for commercial scaled extraction of vegetable oils, for plants processing above approximately 150 tonnes of oilseed a day, is a combination of mechanical extraction, reducing the oil in cake to approximately 20% oil, followed by solvent extraction further reducing the oil in cake to about 1%.

The solvent used in the oil extraction industry is hexane. Hexane is a hydrocarbon solvent and is produced as a by-product in the petroleum industry. The solvent is highly flammable with a flash point of -22°C and is explosive when its vapour mixes with air.

Hexane is not only hazardous due to the threat of fires and explosions in extraction plants, but can also cause serious damage to health if subjected to prolonged exposure through inhalation and adsorption.

Following the extraction of oil from the oilseed the hexane is stripped from the resulting oil and oil cake and recycled to be reused in the extraction process. Solvent loss does however occur during the extraction process, the two main causes being vaporised hexane escaping into the atmosphere and the retention of solvent within the oil cake.

Modern solvent extraction plants will emit approximately 1 kg of hexane into the environment for every tonne of oilseed crushed. This figure represents approximately 1,600 tonnes of hexane emissions per annum in the production of rape oil in the UK alone. Venne (1986) reports that many older solvent extraction plants are less efficient than modern plants resulting in emissions of hexane into the environment, per weight of oilseed processed, 2 to 3 times greater than previously stated.

Over the last few years public awareness and concern over environmental issues has resulted in far stricter environmental regulations throughout the world, particularly in Europe and the USA. In 1990 the US Congressional Amendment to the Clean Air Act listed *n*-hexane as a hazardous air pollutant (Tamelli *et al.*, 1997). De Smet Rosedowns Ltd., oil press manufacturers and the sponsors of this investigation, believe, that within the next decade, emissions of hexane at the levels mentioned above will become unacceptable and new plants will have to dramatically reduce or eliminate these emissions.

The oil extraction industry has long searched for an alternative solvent to hexane not only due to the pending restrictions by regulatory agencies but also because of the high flammability of hexane causing a constant threat of fires and explosions in extraction plants. The 'perfect' solvent has been similarly defined by Jordan (1937) and Mellan (1939), as being, plentiful in supply, low in toxicity, non-flammable, inexpensive, having rapid penetration rate, high solvency power, ease of separation from extracted material, desirable boiling point, low specific heat, low latent heat of vaporisation and high stability.

Lusas *et al.* (1998) state that the reasons why substitute solvents have not been accepted within the industry include, higher long term prices for hexane substitutes, expensive equipment modifications to accommodate hexane substitutes, the petroleum industry providing reliable supplies of hexane at prices acceptable to the extraction industry and safety or toxicity considerations with substitutes. In the United States, the Food and Drug Administration delisted several oilseed solvents because of toxicity concerns (Tamelli *et al.*, 1997).

The lack of success in discovering a suitable replacement solvent to hexane has caused the oil extraction industry to look at improving oilseed preparation treatments to increase efficiency and reduce the solvent retention properties of the oil cake. The industry has also been in search for alternative means to commercially extract oil. Areas of research include supercritical fluid extraction, aqueous extraction, expander technology and the improvement of current mechanical extraction processes. These processes, along with the solvent extraction process have been discussed in more detail in Chapter 2.

Weber (1997) carried out a study to assess the economics of achieving low residual oil content using the solvent extraction process compared to a higher residual oil content achieved with mechanical extraction. Average European levels for the specific costs of investment, utilities and salaries and average achievable prices for meal and oil were used for the study. The results from the study show that a greater cash flow was generated from a solvent extraction plant. The study also suggested that if a mechanical extraction plant is to become profitable it is imperative that animal feed mills will pay a bonus for the extra oil content remaining in the cake.

De Smet Rosedowns Ltd. however consider that there is scope to improve the current mechanical oil extraction process and technology to an extent as to become a commercially viable alternative process for the oil extraction industry. To achieve this goal it is believed that the process will need to achieve the following criteria:-

- reduce the oil in cake after mechanical pressing to between 3 and 4%. As with Weber's (1998) study it is suggested that a premium price for the cake will be achieved due to the higher oil content of the cake and possibly because of the cake containing no solvents.
- reduce energy costs through improved press efficiency and by simplifying the oilseed preparation treatment.
- reduce capital investment requirements for new oil extraction plants again by simplifying the oilseed preparation treatment.

An oil extraction process that meets the above criteria would not only be commercially viable, but would also eradicate the risks associated with the use of chemicals including fire hazards and environmental pollution through emissions and accidental spillage.

1.2 De Smet Rosedowns Limited (Project Sponsor)

De Smet was founded in 1946 in Antwerp, Belgium, when Mr. J. A. De Smet developed the first continuous counter-current solid/liquids extractor for the oil industry. De Smet is now a world leader in the edible oils and oleochemical industry. The company, along with its 17 subsidiary companies, manufacture and install equipment to cover all aspects of the edible oil and oleochemical industry including mechanical preparation and extraction, solvent extraction, oil and fat refining, food processing, waste water treatment, hydrogenation and esterification.

In 1988, De Smet acquired Rosedowns, a manufacturer of mechanical oil extraction equipment based in Hull, UK. Rosedowns were at the forefront in the development of the continuous screw press and today supply both high and low pressure presses, ranging in size from 8 to 500 tonnes per day throughput, throughout the world.

De Smet Rosedowns Ltd. have continued to invest in research and development looking to ever improve the performance and efficiency of the equipment they provide to their customers. As part of their research and development programme De Smet Rosedowns Ltd. have invested in a long term strategic project to further develop the efficiency and performance of the mechanical oil extraction process.

1.3 Summary of chapters

The following section of Chapter 1 states the research hypothesis that has been identified for the research project. The chapter then proceeds to describe what exactly the project is aiming to achieve and identifies the objectives of each phase of the project which will enable the aims of the project to be successfully attained.

Chapter 2 is a non-technical chapter of the research which identifies the importance of competent project management to ensure the successful completion of the project. The chapter then discusses how the phases of project management were used in this research to develop a preparation treatment for the mechanical extraction of oil from rapeseed.

Chapter 3 is a review of published literature carried out to investigate current oilseed preparation and oil extraction process used commercially in the vegetable oil processing industry. The chapter also investigates innovative preparation and oil extraction technologies available to the oil processing industry and how these technologies might be introduced commercially.

Chapter 4 is the project methodology which discusses the experimental plan set to identify the optimum extrusion variables and seed moisture content to maximise the efficiency of the preparation and mechanical oil extraction process for rapeseed. The chapter also details the analysis procedures used throughout the research for analysing residual oil contents, moisture content, the degree of preparation calculated from a milling defect analysis and the effect of the preparation treatment on the microstructure of the seed.

Chapter 5 discusses the set of laboratory scale experiments designed to determine the processing variables or combination of variables that are significant to the preparation process, and to ascertain at what range the variables most enhance the oil extraction process. The aims, objectives and methodology of the set of experiments are detailed along with a description of the equipment used. The results of each experiment is presented and analysed, and discussed in detail at the end of the chapter.

Chapter 6 discusses the set of large scale experiments designed to determine the significance of extrusion temperature on the preparation process and to ascertain at what range the extrusion temperature most enhances the oil extraction process. The chapter also compares efficiency of traditional preparation treatments with the efficiency of extrusion as a preparation treatment.. The aims, objectives and methodology of the set of experiments are detailed along with a description of the equipment used. The results of each experiment are presented and analysed, and discussed in detail at the end of the chapter.

Chapter 7 is a second non-technical chapter which investigates and discusses the economics of oilseed processing comparing the investment and operating costs associated with commercial scaled solvent and mechanical extraction plants. The chapter then discusses the commercial viability of introducing high pressure single screw extrusion as an alternative to the preparation treatments currently employed in the oil extraction industry.

Chapter 8 is a summary of research that compares and discusses the findings from the laboratory and large scale extrusion experiments, and the study of processing economics.

Chapter 9 states the final conclusions drawn based on the findings of the research and finally Chapter 10 states the recommended future work to be carried out.

1.4 Hypothesis

An efficient and industrially competitive process to extract a high quality crude vegetable oil from rapeseed, with a resultant oil in cake content of 3%, can be achieved without the use of a solvent extraction process.

1.5 Aims

A practical programme of work is proposed with the objective to seek a method of extracting oil from rapeseed more efficiently than traditional processes allow. The crude oil is to be extracted from the rapeseed without the use of chemical means. Current methods used for oil extraction involve either a mechanical high pressure press or a mechanical pre-pressing process prior to solvent extraction. The high pressure pressing of rapeseed leaves between 7 and 10% residual oil in the press cake and pre-pressing approximately 20% residual oil in the press cake. It is desired to reduce the oil in residual cake content to 3% omitting the necessity to carry out the solvent extraction process. An efficient process of mechanically extracting oil from rapeseed, with an oil in residual cake content reduced to 3%, will present a competitive and environmentally preferable alternative to solvent extraction most commonly used in commercial oil processing plants.

1.6 Objectives

- Carry out a detailed review of past work relating to the preparation treatment of rapeseed and other oilseeds for oil extraction, and the oil extraction processes available to industry.
- To assess a wide range of processing variables, using a laboratory scale processing operation, enabling the upper and lower limits of the most critical variables for the efficient extraction of a high quality oil to be identified.
- Put into practice and assess a larger scale processing operation based on the information gathered from the previous laboratory experimentation, and identify the optimum machine settings and material conditioning required to efficiently obtain a high oil yield.
- Refine the extraction process for optimum extraction efficiency and oil yield through machine design and process operation.
- Assess the commercial viability of the developed oil extraction process ensuring the sponsoring company a competitive alternative to traditional processing which they can offer to the market.

2. PROJECT MANAGEMENT OF THE 4 YEAR RESEARCH PROGRAMME

2.1 Introduction

A doctorate research degree requires a large amount of planning and control if it is to be successfully completed within a give time scale. A considerable period of time at the initial stages of the research project should be spent clearly defining the objectives of the research and planning how to best achieve these objectives. Chapter 2 discusses project management and its importance in the efficient completion of a project, and describes how the phases of project management were used in this research to develop a preparation treatment for the mechanical extraction of oil from rapeseed.

2.2 Project management

Proficient management of any project is essential if it is to successfully meet its objectives on time and within a predetermined budget. The objectives of the project must be clearly defined from the onset and individual development and implementation stages of the project, required to meet the objectives, need to be thoughtfully planned and closely monitored and controlled throughout the life of the project.

The aim of the project undertaken in this research is to enhance or replace existing technology to improve the efficiency of a current production process. A well managed process development project of this type should include a number of development and implementation phases. The phases of project management are shown in figure 2.1 and are followed with a explanation of each management phase.

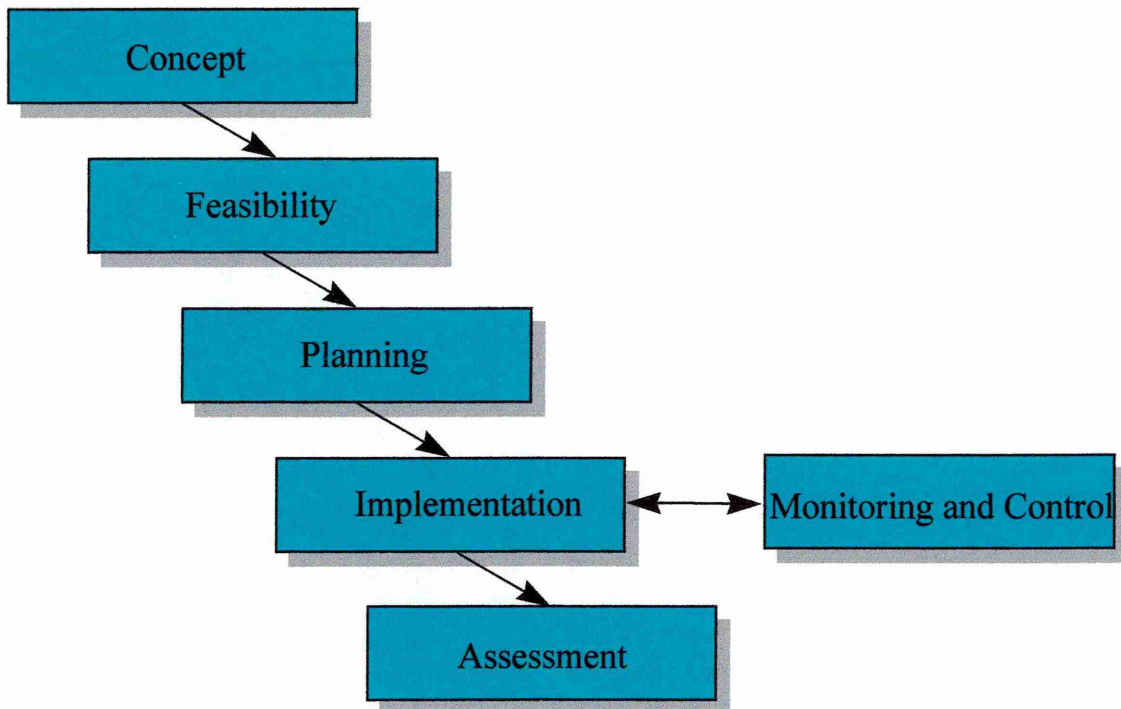


Figure 2.1 *A flow diagram identifying the phases of project management*

1. Concept - At the conceptual stage of the project a company or organisation determines that there is a requirement for a new process. A simple conceptual study is carried out to assess if an idea for developing a process is worthy of investing more time and money.
2. Feasibility - At the feasibility phase of a project the concept is examined in detail to see whether it is a realistic, viable proposition. The feasibility study will include available research facilities, project financing and available time scale. At the end of the feasibility study the objectives of the project should be clearly defined and the viability of the project again assessed to decide whether to proceed with the project.
3. Planning - If the project is considered viable the next phase is to plan the entire project ensuring that the objectives can be met within the time scale and budget.
4. Implementation - Implementation of the project can proceed following its detailed planning. It is important that the project is closely monitored and controlled throughout the implementation of the project to ensure that the project remains on schedule and the objectives are being met.

5. Assessment - At the end of the project the findings of the project must be critically assessed to see if the newly developed process will provide greater performance or economical benefits over existing processes.

2.3 Management of the research project

2.3.1 Project concept

The initial idea for the project was determined by De Smet Rosedowns Ltd. who themselves carried out a conceptual study. The following section describes the project concept and the initial project proposal brought to Cranfield University.

2.3.1.1 Initial project proposal

Solvent extraction is currently the most economic process available for oil extraction on a large commercial scale. Although, on a small scale, mechanical extraction can compete with solvent extraction due to the high initial capital input required for a solvent extraction plant, the lower oil yields associated with mechanical extraction generally prevents the process being a viable commercial alternative. However, environmental issues concerned with the use of solvents in the extraction of oil, discussed in Chapter 1, has made it necessary for the industry to develop or enhance an oil extraction process that reduces or eliminates the requirement of solvents.

De Smet Rosedowns Ltd's. expertise in the development and manufacture of screw presses and experience and knowledge of mechanical oil extraction provides the company with a good commercial opportunity to capitalise on the future constraints associated with solvent extraction and offer the industry a suitable alternative. The company has however identified that if the oil industry is to accede to mechanical oil extraction as an alternative to solvent extraction, it will be essential that the efficiency of the current mechanical process is enhanced.

Two factors that would improve the performance of the mechanical oil extraction process were identified. Firstly, develop and improve the performance of the press or pressing process to increase the oil yield achieved by the process. Secondly, develop an improved preparation process designed to increase the availability of the oil within the prepared seed resulting in a more efficient press, or to reduce the cost of preparation by simplifying or by reducing the energy requirements of the process.

De Smet Rosedowns Ltd. continue to invest in research and development looking to ever improve the performance and efficiency of their press equipment and have many years of experience and expertise in their field. It was therefore considered, from the outset of the project, that the research to be conducted at Cranfield University should utilise the facilities and expertise available to concentrate on the development or enhancement of the preparation treatment of rapeseed for the mechanical extraction of oil. The research on rapeseed preparation would run concurrently with De Smet Rosedowns Ltd's. own on going development of their screw presses in order to enhance the overall mechanical oil extraction process.

Previous to the approach to Cranfield University from De Smet Rosedowns Ltd. with the development proposition, they had carried out a series of trials using extrusion as a preparation for pressing on soybean and sunflower at Wageningen University, the Netherlands, and on soybean, sunflower and rapeseed at the International Soybean Program, University of Illinois, USA. Although the trials at Wageningen and Illinois were too limited to make a comprehensive judgement of the performance of extrusion as a preparation treatment to oil bearing materials for pressing, some promising results were reported which led De Smet Rosedowns Ltd. to suggest that a subsequent investigation into the extrusion process should be carried out.

2.3.2 Feasibility study

The procedure of the feasibility study is described in the following section. The section includes a brief summary of the review of literature that was carried out to investigate oil seed preparation and oil extraction, and of the available research facilities, project budget and time scale available.

2.3.2.1 Role of the literature review in project management

A comprehensive review of literature was carried out to investigate oil seed preparation and oil extraction processes. The study looked at both traditional preparation and extraction processes currently available and widely used commercially in the vegetable oil processing industry as well as innovative processes yet to be established within the industry.

The study of oilseed preparation treatments identified the individual stages of the processes. The investigation identified the purpose of each individual processing stage and the overall effect each processing stage has on the efficiency of the oil extraction process. The study also reviewed the types and uses of extruders and their use in industry. The review of extruders concentrated mainly of their growing use in the oil industry as a preparation treatment of low content oilseeds such as soybean for solvent extraction plants, or of pre-pressed high oil content seeds such as rapeseed and sunflower seed.

A number of factors identified in the desk study suggested that the utilisation of extrusion technology for the preparation of rapeseed could provide an efficient alternative to current preparation treatments. It was considered that by adopting extrusion technology as a preparation treatment for rapeseed the predetermined hypothesis, "an efficient and industrially competitive process to extract a high quality crude vegetable oil from rapeseed, with a resultant oil in cake content of 3%, can be achieved without the use of a solvent extraction process", would be obtainable.

The findings from the desk study were presented to the thesis committee comprising of both representatives from De Smet Rosedowns Ltd. and academic staff from Cranfield University. It was concluded from the presentation of results that the research proposal to investigate the potential for using extrusion as a preparation treatment of rapeseed for pressing should be pursued.

2.3.2.2 *Research facilities*

Facilities available to carry out the research project together with the available research budget needed to be assessed prior to identifying the scope of the project.

Two single screw extruders were available for use. The first extruder being a small Brabender laboratory extruder with a 19 mm barrel diameter, and the second, a larger 32 mm barrel diameter Almex extruder. De Smet Rosedowns Ltd. made available a prototype mini 100 screw press. The equipment is discussed in greater detail in Chapters 5 and 6. Seed milling and cooking equipment was available providing the means to simulate traditional preparation treatments.

The university laboratories were equipped with the standard equipment for analysing oil contents, moisture contents and material microstructures with light microscopy. Laboratory equipment to analyse oil quality was not however available therefore the quality of extracted oil under different process conditions was beyond the scope of the research.

The research budget available for the project was £10,000 spread over a four year period. Items covered within the operating budget included equipment installation and repair costs, manufacturing costs, specialist equipment purchases, laboratory costs and consumables including rapeseed. The budget was closely monitored and managed throughout the research period.

2.3.3 Project planning

A work schedule for the research project was developed which considered all aspects of the research project including equipment and research facility availability, manufacturing requirements, experimental procedures and the taught element of the engineering doctorate (EngD) programme. The development of a work schedule is detailed in the following section.

2.3.3.1 *Work schedule*

The EngD is a four year programme consisting of both taught elements and a commercially related engineering research project. Time management is an important determinant in the successful completion of both the research project within the set time constraints together with the taught element required for the fulfilment the doctorate programme. When planning work schedules the ultimate goal of the project should be defined and the major stages of work, in order to achieve this goal, identified. Realistic time scales for each stage need to be planned taking in to account any foreseeable factors that could determine the time requirement for the work including manufacturing time, equipment availability, technician availability and delivery times.

Work schedules were developed from the onset of the project identifying the major stages of the programme with start and completion target dates. The timetable for the taught element of the doctorate programme was mainly predetermined and fixed which had to be considered during the planning.

The taught element of the programme was divided in to two parts, management and engineering. The taught management element, consisting of the core subjects of a Master of Business Administration (MBA), was mostly time tabled for the first 6 months of the programme. The remaining management training and engineering taught element was completed on either a seminar or course basis throughout the 4 year programme.

The major stages of the research programme were identified as the management training, initial project proposal, literature review, research proposal, planning, two major experimental stages consisting of laboratory scale and large scale experiment design, analysis and finally the write up. The design and planning of the individual experiments within each major experimental stage was results led and therefore was to be determined during the research period. The specific breakdown of the experimental stages was therefore not possible at the onset of the programme. The work schedule for the programme can be seen in Appendix A.

2.3.4 Implementation

With the research proposal and initial experimentation plan endorsed by the thesis committee it was possible to proceed with the experiments as planned in the work schedule. Two major experimental phases, a laboratory scale experiment block and a large scale experiment block, were carried out and are described in Chapters 5 and 6 respectively.

2.3.5 Planning, monitoring and control

Following each experiment, in both the laboratory and large scale block of experiments, the results were analysed before deciding on the content of the subsequent experiment. The experiment planning was results led giving the flexibility to act on significant findings. At any major juncture in the progress of the research previous results and the proposed future direction of the work was presented and discussed with the thesis committee. The thesis committee meetings provided the opportunity to closely monitor the progress of the research and control the direction in which it progressed.

The nature of a research project, not knowing exactly what direction the project is going to take between each set of experiments, requires a level control to ensure that the research continues to aim towards the ultimate goal set out in the initial stages of the project. It was therefore important that the progress of the research was closely monitored throughout the length of the project to ensure that the initial work schedule was adhered to.

2.3.6 Project assessment

The final phase of a research project when developing a new process is to critically assess the findings of the project to see if there is sufficient justification, be it through enhanced process performance or a potential for economical benefits, to recommend that the newly developed process replace existing commercial processes.

3. LITERATURE REVIEW

3.1 Introduction

A review of published literature was carried out to investigate current oilseed preparation and oil extraction processes used commercially in the vegetable oil processing industry. The study also looked at innovative technologies available to the industry and how these technologies might be introduced commercially.

The chapter first discusses the importance of rapeseed as a globally produced crop and the importance of the extracted rapeseed oil for both industrial use and for human consumption.

The preparation treatments and extraction process for mechanical oil extraction and solvent extraction, the two major oilseed processing methods currently used in the oil processing industry, are discussed in detail. A critical analysis has been carried out to investigate how the individual preparation treatments of seed flaking and conditioning enhance the oil extraction process.

The innovative oilseed preparation and extraction processes, super critical fluid extraction, enzyme treatments and aqueous extraction, are briefly explained identifying the potential benefits and disadvantages of introducing the processes into the oilseed processing industry on a commercial scale.

The final section of the chapter introduces extrusion as a versatile processing technology, the use of which is growing in many industries including the oilseed processing industry where it is more commonly being used as a preparation treatment of low oil content oilseeds for solvent extraction. The benefits of the process and the potential of the technology as a preparation treatment of rapeseed for the mechanical extraction of oil with a screw press is then discussed.

3.2 Oilseed rape

World vegetable oil trading is dominated by the production of palm oil, mainly in Malaysia and Indonesia, and soybeans in the USA and South America. However, over the last 20 years, the production of rapeseed has increased dramatically. In terms of production, it is currently the third most important oilseed crop in the world after soybean and cottonseed as illustrated in Table 3.1 (Scarbrick *et al.* 1995).

Table 3.1 *Approximate world oilseed production (million tonnes)*

	1990/91	1993/94
Soybeans	102	113
Cottonseed	34	33
Rapeseed	26	28
Sunflower seed	23	23
Groundnuts	24	23
Linseed	3	3

Source: Commodity Review and Outlook 1993/94, FAO (Scarbrick et al., 1995).

Commercial oilseed rape is the product of several species belonging to the genus *Brassica*, family *Cruciferae*. The four most commercially significant oilseed varieties belonging to the genus *Brassica* are *B. napus*, *B. campestris*, *B. juncea* and *B. carinata*. (Scarbrick *et al.*, 1995) Oilseed rape is classed as a high oil content seed with an oil content ranging from 42-46%.

The major production areas for *B. napus* (Swede rape) and *B. campestris* (Turnip rape) are Europe and Canada with *B. juncea* (Mustard rape) mainly produced in the Indian subcontinent and China and *B. carinata* (Ethiopian rape) produced in Ethiopia and east Africa (Scarbrick *et al.*, 1995).

Rapeseed is reported to have been grown in the UK since the mid sixteenth century and by the end of the seventeenth century the oilseed crushing industry was of significant importance. The oil was extensively used for lamp oil and the meal for cattle food (Scarisbrick *et al.*, 1986).

By 1850, mineral oil largely replaced rapeseed for lighting and lubrication and by the mid 1930's rapeseed had become of minimal importance in world trade (Scarisbrick *et al.*, 1986).

After the second world war a world shortage in vegetable oils led to the regeneration of the rapeseed industry with Canada and Europe joining China and India as the major rapeseed producers (Scarisbrick *et al.*, 1986).

The development of oilseed rape as a competitive oilseed in the early 1970's was limited by two factors, the high content of long chain fatty acids (mainly erucic acid) and glucosinolates in rapeseed cake (Scarisbrick *et al.*, 1995). The high content of erucic acid in the oil, although providing the oil with important lubricating properties for certain industrial uses (Carr, 1990), does make the oil unsuitable for use as an edible oil (Scarisbrick *et al.*, 1986). The breakdown of glucosinolates in rapeseed, by the enzyme myrosinase (Scarisbrick *et al.*, 1986), during the oil extraction process produces by-products that lower the palatability of the meal and produces a range of nutritional disorders in farm livestock (Scarisbrick *et al.*, 1995).

During the mid-1970's varieties of rapeseed were developed with erucic acid as low as 5%, by 1978 this had been reduced to below 2% and has since been reduced to the present level of as little as 0.6% erucic acid (Carr, 1990). The introduction of 'double zero' varieties (low in erucic acid / low in glucosinolate) in the late 1980's had a major impact on world oilseed markets. The removal of erucic acid and glucosinolates allowed the oil to be used as an edible oil for human consumption and made the meal acceptable for stock feed.

3.3 Uses for oilseed rape

Oil extracted from rapeseed has many uses in industry, food production and as a fuel.

3.3.1 Industrial usage

Rape oil and its derivatives have many uses in industry. The presence of long-chain fatty acids in high erucic acid rapeseed (HEAR) give the oil excellent lubrication properties (Scarbrick *et al.*, 1986). HEAR oil is used as slip agents in the polymer industry and in the production of behenyl alcohol which is used as a flow improver for waxy crude mineral oil (Walker *et al.*, 1993).

Oil from “double zero” varieties of rapeseed are also widely used for industrial purposes including the paints, plastics, lubricant adhesive and pharmaceutical industries (Scarbrick *et al.*, 1995; Walker *et al.*, 1993; Sandars, 1995 and Ward *et al.*, 1985).

3.3.2 Food production

Rapeseed oil is used extensively in the food industry in the manufacture of salad dressings and table oils, confectionery, shortenings, margarine and low fat spreads, dairy based products and ice cream, soups and as a pure cooking oil (Ward *et al.*, 1985 and Podmore, 1986).

Physical properties of rapeseed oil make it superior to other oilseeds oils for certain applications within the food industry. When properly produced rape oil is both colourless and tasteless and has important viscosity and solidification and melting properties (Ward *et al.*, 1985). Rape oil also has very good dietary and nutritional properties being low in saturated fats and high in monounsaturated fats as illustrated in Table 3.2.

Table 3.2 *A Comparison of dietary fats*

Dietary Fat	Saturated Fat	Polyunsaturated Fat		Monounsaturated Fat
		linoleic acid	linolenic acid	
	(%)	(%)	acid (%)	(%)
Rapeseed oil	6	26	10	58
Safflower oil	9	78	Trace	13
Sunflower oil	11	69	-	20
Corn oil	13	61	1	25
Olive oil	14	8	1	77
Soybean oil	15	54	7	24
Peanut oil	18	34	-	48
Cottonseed oil	27	54	-	19
Lard	41	11	1	47
Palm oil	51	10	-	39
Beef tallow	52	3	1	44
Butterfat	66	2	2	43
Coconut	92	2	-	6

Source: Agricultural Handbook No. 8-4 and Human Nutrition Service, United States Department of Agriculture, Washington DC 1979 (Walker et al., 1993).

Consumption of high levels of saturated fatty acids has been associated with elevated cholesterol levels constituting a major risk in coronary heart disease (Walker *et al.* 1993). Rape oil has a lower saturated fat content than any other commonly used vegetable oil (Booth *et al.* 1994), therefore, in this respect, rape oil is more attractive than both olive oil and sunflower oil which are perceived, by the consumer, as the most healthy (Walker *et al.*, 1993).

Consumption of unsaturated fatty acids (94% of fatty acids in rape oil) either do not increase levels of cholesterol or may even lower them (Sanders, 1994). This would tie in with the statistics showing populations consuming the “Mediterranean diet”, characterised by the intake of high levels of monounsaturates from olive oil, are far less susceptible to chronic heart disease than populations consuming the “Western diet” high in saturated fatty acids (Walker *et al.*, 1993 and Booth *et al.* 1994).

Conclusions from the conference on “Rapeseed Oil in Human Nutrition”, Stockholm, 1992, concluded that rape oil was as effective as other oil high in polyunsaturated fats in lowering cholesterol levels and its present fatty acid composition was considered to be close to the nutritional ideal (Booth *et al.*, 1994).

3.3.3 Biodiesel

Fuel manufactured from vegetable oil has immense environmental advantages over mineral oil fuels for use as a transport fuel. These advantages are:

- Vegetable oils are an annually renewable source of energy (Walker, 1995).
- Exhaust emissions are greatly reduced with sulphur dioxide emissions virtually eliminated (Walker, 1995 and Culshaw, 1993).
- High biodegradability (Walker, 1995 and Culshaw, 1993).
- Low toxicity against water plants, fish, algae and bacteria (Walker, 1995).

Rapeseed oil has been targeted to produce biodiesel for its stability, its characteristics as a fuel at low temperatures and its ignition properties (Walker, 1995).

Rape oil can be used easily in a pure form in indirect injection compression ignition engines or converted to an ester (rape methyl ester, RME) for use in modern diesel engines (Walker, 1995).

3.3.4 Animal feed

Protein meal is produced as a by-product of the crushed rapeseed and is widely used for livestock feed.

3.4 Current oil extraction methods

3.4.1 Oilseed preparation

The preparation treatment of oilseed for extraction are very similar for both solvent extraction and mechanical extraction, the principal extraction processes used in industry today.

The initial oilseed preparation stage for oil extraction is cleaning. For this process the oilseed goes through a number cleaning stages to ensure that seed is free of contamination from dockage, volunteer seed, stones and dirt. The cleaning process incorporates the following stages:

- Aspiration and sieving to remove trash.
- Indented cylinder machines eliminating seeds which are longer / bigger than the rapeseed.
- De-stoners to remove dirt balls and small stones.
- Specific gravity tables to remove particles the same size but varying density to the seed.

Following the cleaning stages, the oilseed undergoes a number of preparation stages to restructure the seed improving its properties for the solvent and / or mechanical extraction of the oil.

Oilseeds are heated and passed through a roller / flaking machine to fracture the seed coat and rupture the oil cells. Ward (1984) reported that Rosedowns Ltd. investigations show that the reduction of the rapeseed cell structure is desirable but not nearly as important as breaking the seed coat of virtually every seed. The failure to break the seed coat results in the presence of whole seed in the press cake which reduces the efficiency of the extraction process leaving a higher percentage oil in cake. When using solvents to extract oil, whole seeds left in the press cake increases solvent retention (Ward, 1984). For solvent extraction, the resulting flakes of seed are only a few thousandths of an inch thick (Scarisbrick *et al.*, 1986).

Preheating cold seed is a practical necessity to prevent the seed from shattering during flaking. It also serves to reduce the power on the flaking rolls and remove elasticity from the seed (Ward, 1984).

At low seed moisture content the formation of fines can occur during seed flaking. It is important that the formation of fines does not occur as it will lead to difficulties in the extraction and clarification of the crude oil. To avoid this phenomenon a minimum moisture content of 6-8% is maintained (Niewiadomski, 1990).

Power consumption during rapeseed flaking depends on the equipment used and varies from 2.4 to 3.5 kWh/t of raw material depending on the degree of heating. Flaking rollers are an energy efficient way of breaking the seed with upwards of 90% of power input at the flaking rolls appearing as heat, reducing the subsequent heating requirements (Ward, 1984).

Unlike some other oilseeds, rapeseed is not dehulled as a preparation treatment as rape has a relatively high oil content in the hull. Dehulling would result in approximately 6-7% loss of oil.

Immediately after rolling, seeds are transferred into a stack cooker and heated to approximately 70-100°C. Seeds should not in any event be stored in a flaked/crushed state (Niewiadomski, 1990).

The cooking process :-

- ruptures any intact oil bearing cells still remaining within the seed which facilitates optimum oil release during processing (Mag, 1994);
- coalesces small oil droplets to larger ones (Mag, 1994);
- denatures proteins to facilitate separation of the oil (Scarbrick *et al.*, 1986);
- renders insoluble some of the natural phosphatide “gums” (Scarbrick *et al.*, 1986);
- reduces oil viscosity, allowing it to flow more readily from the meal. Pores in the meal are very much reduced during pressing, therefore, the resistance to flow must be minimised (Ward, 1984);
- destroys many resident moulds and bacteria (Scarbrick *et al.*, 1986);
- detoxifies undesirable seed constituents such as cottonseed and gossypol (Ward, 1984);
- lowers moisture content (Scarbrick *et al.*, 1986);
- coagulates protein for better diffusion during solvent extraction (Mag, 1994);
- deactivates enzyme systems within in the seed (Mag, 1994).

The coagulation of the protein and the elimination of enzyme reaction are time, temperature and moisture content dependent (Ward, 1984).

The rolled seed is heated in the cookers as rapidly as possible to 90°C to destroy the myrosinase, the enzyme system that causes the hydrolysis of glucosides. Hydrolysis is particularly rapid at 50 to 70°C. Moistures over 10% can speed hydrolysis of the glucosides during heating and low moisture content hinders the destruction of myrosinase, therefore, it is aimed to achieve a moisture content of about 8% when the seed enters the cooker (Leslie *et al.*, 1974). However, with the developments of low glucosinolate variety rapeseed, this phenomenon will become less important.

Steam consumption (at 10.5 bar) in cooking rapeseed (from 16°C), including heat input at any preheating stage, is 65 - 120 kg/ton, depending on the degree of drying. Power consumption in a stack cooker ranges from 1.9 to 3 kWh/t (Ward, 1984).

Subsequent processing will depend on the extraction process being used.

3.4.2 Solvent extraction

Following the previously explained oilseed conditioning processes, namely rolling and cooking, the oilseed is subjected to a low pressure pressing prior to solvent extraction.

The pressing process is described in detail in section 3.4.3

Low pressure screw pressing reduces oil content of the seed from about 45% (8% moisture basis) to 16-20% mechanically and compresses the conditioned oilseed meal into large cake fragments (Mag, 1994). The power requirement for low pressure pressing has been calculated at 10.2 kWh/t (Ward, 1984). The extra cost of low pressure pre-pressing is justified by the fact that solvent extraction of the remaining oil is much more efficient and economical following pressing than extracting oil straight from cooking.

The processing of the seed up to the point of solvent extraction must produce a press cake with good extractability and percolation properties. Some factors governing these properties are (Ward. 1984):

- Uniformity of particle size.
- Presence of whole seed or large particles of uncrushed seed.
- Oil and moisture content of the cake.
- Porosity of the cake.

Oilseed cake is conveyed into a solvent extractor where the solvent (hexane) is added to the cake. The solvent leaches the remaining extractable oil forming miscella (oil and hexane mixture). Miscella and cake are separated in the extractor and fed through a solvent recovery system where the hexane is recovered from the oil and cake. Rapeseed extracted meal is one of the most difficult to desolventise and a residual figure of 1000 PPM hexane in the cake is considered good by many operators. Solvent extraction is however an efficient process in extracting oil from rapeseed producing a residual oil in cake as low as 1%.

Solvent extracted oil is combined with pre-pressed oil and refined for its particular use.

There are however a number of drawbacks with the use of solvent extraction plants. Solvent extraction plants involve a high initial capital investment and have to be on a large scale to become commercially viable. Such investment often make solvent extraction impractical for use in developing countries, where high quantities of oilseed are produced.

3.4.3 Mechanical Extraction

In a mechanical oil extraction process, oil is separated from the rolled and cooked seed by high pressure screw pressing (figure 3.2). Screw presses work on the principle of pressure differential applied to the feed material versus that applied to the discharged cake (Singh *et al.*, 1990).

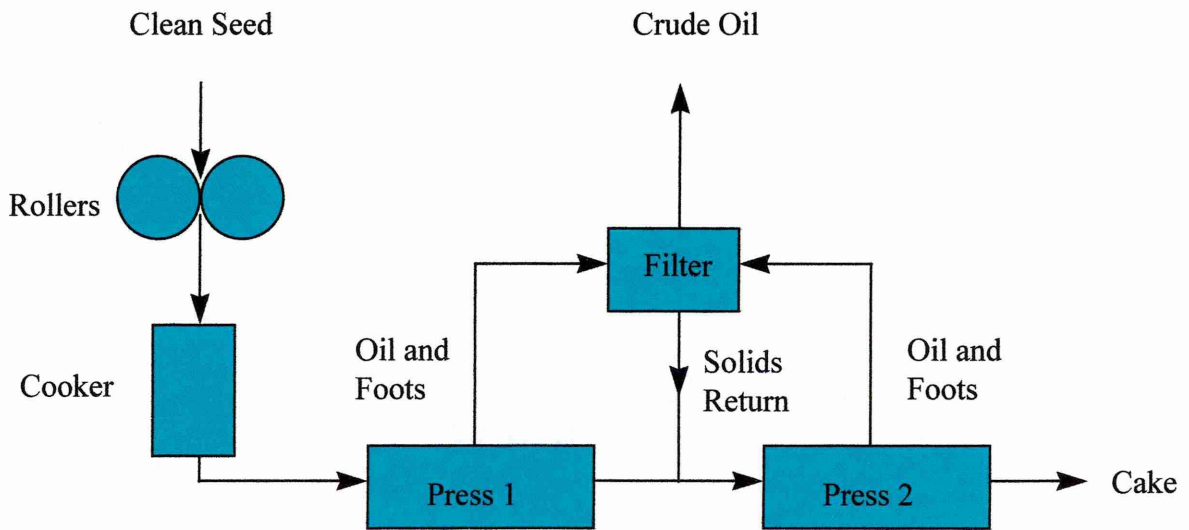


Figure 3.2 Operational stages of a typical commercial vegetable oil mechanical extraction process plant.

The major components of a screw press are a press cage within which is located a rotating press screw.

The press cage is constructed of cage bars with spacers between to allow for drainage of the oil.

The press screw fits in the cage with a minimal clearance between the screw flights and cage bars. Prepared oilseed is fed in the feed end of the press on to the screw and the rotating action of the screw transports the oilseed along the length of the press. The screw is designed to continually shear and exert radial pressure on the oilseed through volumetric compression resulting in oil being squeezed from the oilseed.

The volumetric compression results in a steep pressure gradient from the feed end of the press. This results in the oilseed meal having to be fed forward against a rapidly increasing pressure which causes the meal to slip and rotate with the screw (Ward, 1976). The rotational slippage of the meal is detrimental to press performance reducing throughput and increasing the required compression ratio of the screw assembly. Ideally there should be no rotation of the meal within the press screw but only axial movement (Singh, 1990). Ward (1976) gives the following example to demonstrate the fact.

100 lb. of groundnuts fed to the press at 33 lb./ft^3 would produce 55 lb. of cake at a voidless density of 80 lb./ft^3 in a high pressure pressing operation. Hence, the volume at feed divided by volume at discharge equals 4.3, which is the theoretical compression ratio. However, the actual compression ratio used is in the order of 10:1.

If the oilseed meal could be preconditioned to enable the screw to improve the grip of the meal, rotational slippage within the press chamber could be reduced and axial flow enhanced, in turn improving press performance.

Singh (1990) states that screw pressing of high oil content seeds, i.e. rapeseed, requires a high compression ratio in the order of 10:1

Commercial high pressure screw presses exert a maximum pressure in the range of 100-150 MPa (Vivek *et al.* 1988) and can reduce the oil in cake to about 8%. However, high pressures exerted on the oilseed during screw pressing is not the optimum condition for efficient oil extraction.

It was stated by Ward (1976) that the screw pressing operation is ultimately self-defeating. Oil in the oilseed is contained in sacs or fibrous capillaries. The application of pressure causes the capillaries to be reduced in volume and the oil to be expelled, but, by the same effect, the capillaries are narrowed, sheared, and eventually sealed by the application of increasing pressure. Ward suggests that this puts a practical limit on the lowest residual oil in cake content that can be achieved with high pressure screw pressing, even with the other operations ideally performed.

The self defeating effect of high compression ratio screw pressing described by Ward (1976) has promoted a change of thought on screw press design with modern screw presses designed with considerably lower screw compression ratios than stated by Singh (1990).

It is agreed that there is a practical limit on the efficiency of screw pressing, but with current oilseed preparation treatments this limit has not yet necessarily been achieved.

Stein (1984) suggests that there is no oil recovery whatsoever without cracking the cell walls as they are impenetrable to oil and that the maximum extraction rate is limited by the rate of cell cracking in the oilseed, i.e. the efficiency or degree of preparation. The degree of preparation may be found from the following:-

$$X^t = 100 - 100 \frac{x - x'}{x_o} (\text{wt } \%)$$

x_o = oil content of seeds

x = oil content after separation

x' = minimum oil content after separation

To achieve a residual oil content of below 1%, the degree of preparation must be in the range of greater than 98%.

Mrema *et al.* (1984) contradicted Steins (1984) statement however and have offered proof confirming the hypothesis that oil expression from oilseed can occur through their porous microstructure without cell wall rupture. Microstructure studies of rapeseed using transmission electron microscopy revealed plasmodesmata, of mean diameter 87 nm, scattered over the cell wall surface with a mean frequency of 0.156 plasmodesmata per μm^2 giving an average porosity of the cell walls of 0.093%.

A mechanical expression rig was used in experimentation to enable a comparison between the microstructures of oilseed before and after oil expression. Observations confirmed that the cell walls of rapeseed were still intact subsequent to oil expression. The test was also carried out with cashew which has a similar overall cell structure to rapeseed and other oilseeds like soybeans, cottonseed and peanut. Observations show that the cell walls of the cashew were un-ruptured in a processed cashew and in cashew from which 80% oil had been expressed. This was equally true whether oil expression occurred at ambient temperature or after preheating to 120°C for 1 hour (Mrema *et al.*, 1984).

A further experiment carried out by Mrema *et al.* (1984) revealed that when oilseed cake was compressed in undrained loading, extensive cell wall rupture was observed.

The work by Mrema *et al.* would suggest that traditional oilseed preparation treatments of milling and cooking are not effective in producing a meal in the optimum condition for oil expression. If a preparation treatment process that applied undrained loading to the oilseed, rupturing its cell walls, it is suggested that the performance of mechanical oil expression could be enhanced.

Much work has been done by the industry to identify the effects oilseed preparation has on press performance and operating efficiency but a full understanding has not yet been achieved for all seeds.

Singh *et al.* (1984) observed that moisture content was the most important factor effecting the expression of oil from sunflower seed. This view has been corroborated by most of the other workers quoted in this chapter.

Stein (1984) states that for pressing, moisture content has two countercurrent effects. Firstly, water works as a lubricant giving a lower build up of pressure at higher moisture content thus resulting in higher residual oil content. Secondly, water eases flux of oil through pores and capillaries at higher moisture content resulting in lower residual oil content. Vaughen (1970) suggests the moisture content effects pressing efficiency through mucilage development in the outer epidermal cells of the oilseeds impeding the flow of oil from the cotyledon tissue.

The optimum moisture content for oil expression varies with different oilseed types. Maximum oil expression from conophor nut was observed at 8-10% moisture content (dry basis) (Fasina *et al.*, 1989), from sesame seed at 6% (dry basis) (Ajibola *et al.*, 1993), and from melon seed at 5% (dry basis) (Ajibola *et al.*, 1990).

Work done at the University of Saskatchewan, Canada, using a lab scale screw press to express oil from canola, observed that the maximum pressure in the press dropped slightly as seed moisture was increased from 4% to 5% and sharply thereafter. They also observed that maximum press throughput and oil output occurred at 5% moisture and the lowest residual oil in the presscake occurred at 4% seed moisture (Vivek *et al.* 1988).

Heating and flaking are also important preparation treatments and have been detailed in oilseed preparation, Section 3.4.1.

Vivek *et al.* (1988) summarised the qualitative effects of canola seed pretreatments on pressure within the press, press throughput and residual oil content in the press cake. The summary is shown in figure 3.3.

Variable		P	Q'	RO
Seed Treatments				
Heating	↑	↑	↑	↓
Flaking		↑	↑	↑
Flaking + Heating	↑	↑	↑	↓
Moisture Addition	↑	↓	↓	↑

Figure 3.3 Summary of qualitative effects of canola seed pretreatments on pressure (P), throughput (Q') and residual oil content (RO).

The process of straight pressing has advantages over solvent extraction plants of lower investment costs and of achieving higher quality oil. Furthermore, if the oil present in the press cake increases its price relative to the price of solvent extraction meal, then the straight pressing method will successfully compete with the pre-press / solvent extraction method (Niewiadomski, 1990).

The disadvantages of screw pressing are high power consumption, wear, equipment maintenance, and high residual oil in meal (Peterson *et al.*, 1983).

3.5 Alternative Preparation and Extraction Processes

A number of alternative processes for the preparation and extraction of oil have been researched. Although some promising results have been produced from these alternative processes, they have not been taken on board by the oil industry for large scale commercial processing.

A description and the effectiveness of some of the alternative processing extraction methods are detailed below.

3.5.1 Aqueous Extraction

An example of the process systems involved in aqueous extraction are shown in figure 3.4 The process is claimed to give a high quality crude oil superior to that obtained from traditional solvent extraction processing. The process is not however as efficient as solvent extraction leaving a higher residual oil in cake.

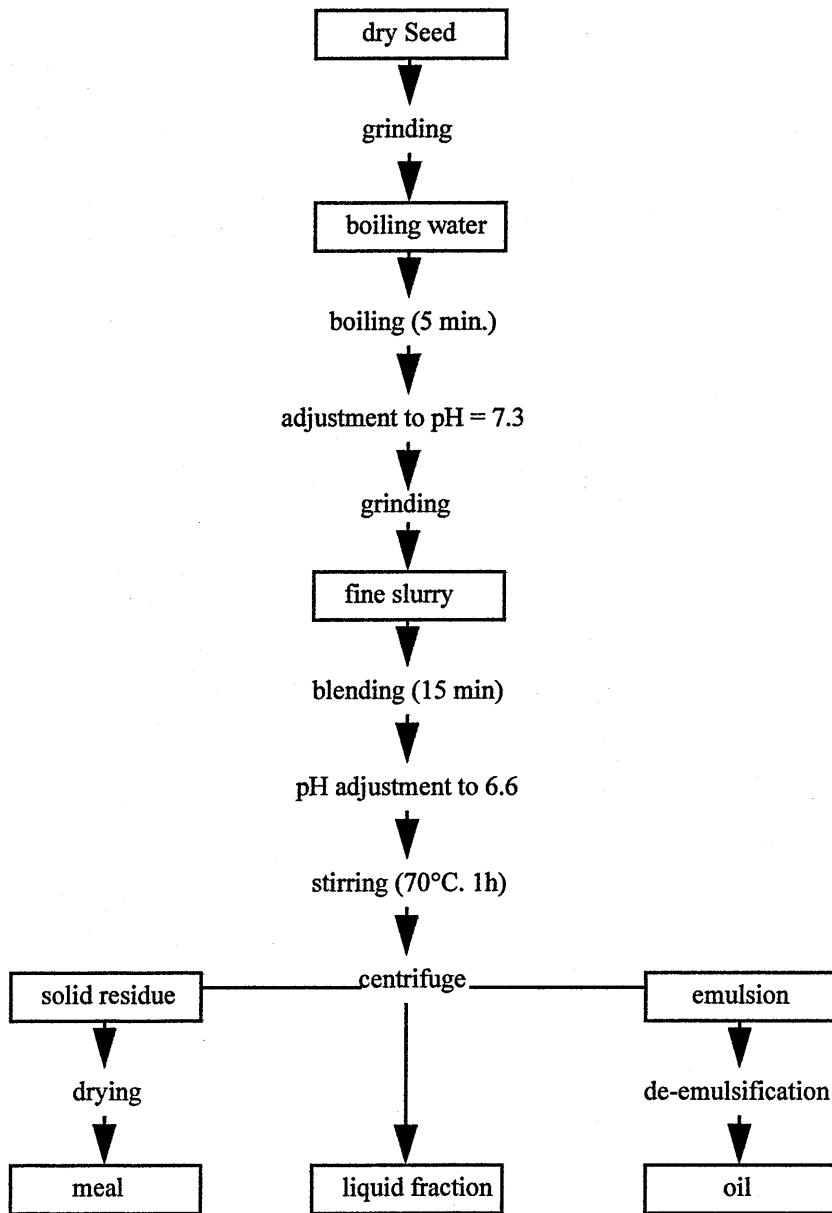


Figure 3.4 Flow diagram for the aqueous processing of rapeseed (Niewiadomski, 1990).

Hagenmaier (1972) reported on aqueous processing of sunflower seeds. The sunflower seed was first flaked and then finely ground in a disc attrition mill prior to the aqueous extraction. During the extraction 0.2 % of sodium sulphite was employed to inhibit colour change. A fresh solution of sodium sulphite was mixed to the ground seed to give a 10:1 solution to seed ratio.

The mixture was adjusted to the desired pH value with NaOH or HCl solutions, with stirring and readjustment continuing for 45 minutes. The solids were separated from the liquid, containing the aqueous phase and oil and water emulsion, using a basket centrifuge. Finally the oil and aqueous phase were separated with a disc-type three phase centrifuge.

Hagenmaier's (1972) findings suggest that the efficiency of the oil extraction process was dependent on pH, with the optimum efficiency achieved at pH 10, extracting 86 % of the available oil.

3.5.2 Enzymatic Decomposition of Seed Tissue

The use of enzyme systems from microbial sources as an extraction process or as a preparation treatment for the processing of oilseeds are gaining in importance.

Sosulski *et al.*, (1988) reported that pre-treating canola with carbohydrases reduced extraction time in the solvent extractor and increased oil yield. The optimum pre-treatment prior to extraction with hexane was found to be flaking, autoclaving, adjustment of seed moisture to 30 % (including 0.12 % enzyme concentration), and incubation for 12 hours at 50°C followed by drying to 4 % moisture content.

Sengupta (1996) reported on the enzymatic extraction of mustard seed and rice bran and stated that certain enzyme systems are capable of actions on constituents of oil bearing materials. The enzymes controlled activities on proteins, cellulose and hemicellulose allowing oil globules to be readily released. *Bacillus subtilis* and *Aspergillus niger* are two organisms which have the desired enzyme systems and have been examined for the extraction of rapeseed and soybean (Sengupta, 1996).

It is claimed that the advantages for the use of enzymes in processing oilseeds are low energy consumption and solvent usage, higher nutritive value of protein and extremely good quality oil, requiring no refining after extraction (Sengupta, 1996).

A control experiment was carried out to examine enzymatic extraction of mustard seed. The results show that a good quality oil was extracted, and it appears that the process is effective for achieving almost full recovery of oil from mustard seed (Sengupta, 1996).

There are however disadvantages of using the enzymatic decomposition of seed tissue as a preparation treatment for solvent and possibly mechanical extraction restricting their suitability for commercial use. The disadvantages include a high cost for the enzymes, largely due to the high cost of researching and developing enzyme systems, and the length of time required for the enzyme treatments to work, making the process impractical for commercial use.

3.6 Supercritical fluid extraction

Supercritical fluid extraction (SCFE) is a process where a solvent is contacted with a solute at conditions near or above the critical point of the solvent plus solute mixture. The solubility characteristics of solvents are enhanced at or near its critical point. This together with the ease of separation of the solvent from the solute for recycling is making SCFE processes increasingly popular in a number of industries.

A popular solvent for the food industry is CO₂ because it is non-toxic, non-flammable, non-corrosive, inexpensive, readily available in high purity, and is easily handled and removed from the products due to it having a critical temperature little above ambient. The critical properties of supercritical CO₂ are temperature, (T_c , 31.2 °C) and pressure, (P_c , 7.38 MPa) (Wang. *et al.* 1995). The basic components of a SCFE process are shown in figure 3.5.

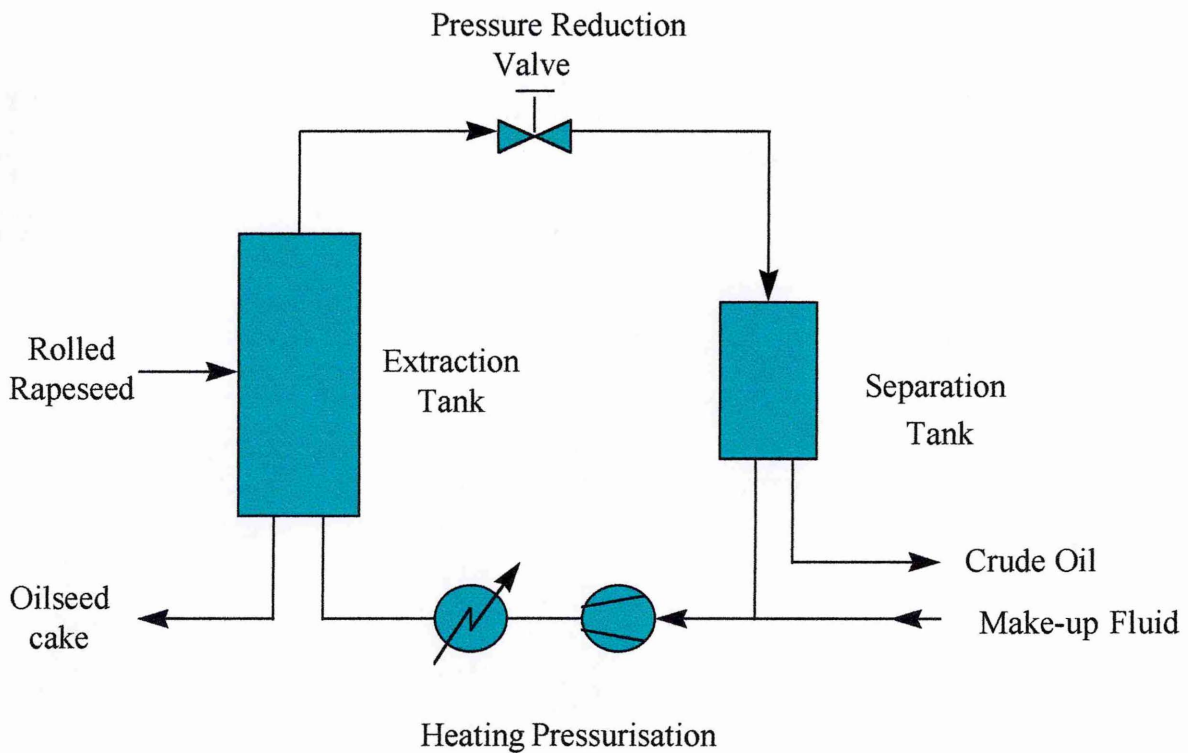


Figure 3.5 Basic components of a SCFE process (Dincer *et. al.* 1997)

Gaseous CO₂ is condensed in a compressor $> P_c$ and heated $> T_c$. The supercritical carbon dioxide (SC-CO₂) then flows to the extraction tank containing the rolled seed. Following the extraction process the pressure within the system is reduced to $< P_c$ returning the CO₂ to gas and thus separating it from the oil. The gas is then re-condensed and the cycle can be repeated.

Stahl *et al.* (1980) reported that between 96 % and 98 % of the available oil can be extracted from ground rapeseed with liquid or supercritical CO₂.

Fattori *et al.* (1988), (cited in Temelli *et al.* (1997)), studied the effect of extraction conditions on canola solubility in SC-CO₂. The highest oil solubility was achieved at an extraction pressure of 36 MPa and temperature 55 °C.

Dincer *et al.* (1997) claims there are two major disadvantages with SCFE. Firstly, each new application for SCFE requires extensive experimentation as the models for prediction of solubility are not satisfactory due to the complexity of phase equilibria near the critical point. Secondly, the initial investment and maintenance costs are high because of the high pressures required in the process.

3.7 Extrusion

Extrusion cooking is a single process that combines the operations of continuous feed transport, mixing, cooking, forming and shearing under high pressures. Extrusion technology could offer a means of preparing an oilseed, utilising the processes capabilities to continuously heat and shear the oilseed in a single operation, providing a potential improvement over other grinding and heating systems traditionally used in the oil processing industry.

The following section describes the extrusion cooking process giving a description of the equipment and the classification of the different types of extruder. Finally, the section identifies how extrusion technology is currently being used in the oil processing industry and concludes with a discussion on how the process may be utilised in the preparation of rapeseed for the mechanical extraction of oil.

3.7.1 Extrusion process

Over the last few decades extrusion technology has played an ever increasing role in many industries including the food, polymer and feed processing industries (Li *et al.*, 1996).

Food extrusion can be described as a process in which a food material is forced to flow under one or more of a variety of conditions of mixing, heating and shear through a die which is designed to form and / or puff dry the extrudate (Miller, 1973 cited in Badrie, 1990) .

The use of a single screw extruder in the food processing industry has many advantages over traditional processes. The advantages have been listed by Harper (1978) as follows:-

- Machine versatility
- High productivity
- Low cost
- Product shaping
- High product quality
- Energy efficient
- Food modification
- No effluents

3.7.2 Components of a single screw food extruder

A single screw food extruder consists of a close tolerance flighted Archimedes screw which rotates in a barrel. The rotating screw, relying on drag flow, transports the feed material to the discharge end of the extruder where the extrudate is forced through a small orifice (Harmann *et al.*, 1973 and Harper, 1978). A sectioned line diagram of the main components of a single screw extruder can be seen in figure 3.6

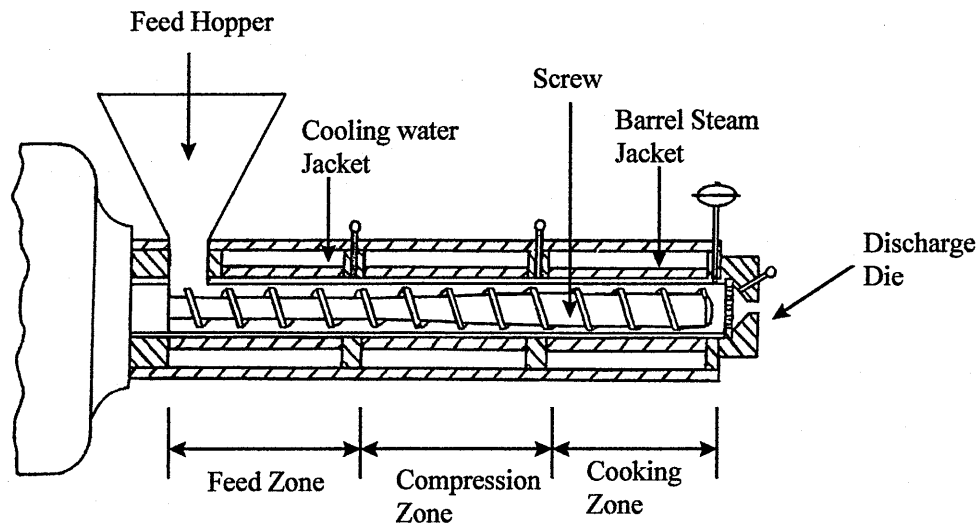


Figure 3.6 A sectioned line diagram of the main components of a single screw extruder.

The main components of a single screw extruder are described below.

1. Extrusion Drive - Variable speed usually driven by an electric drive motor.
2. Feed Assembly - Feeds material into the extruder. Type of feed assembly will depend on the feed material.

3. Extruder Barrel - Fits tightly around the rotating extruder screw. The extruder barrel is often surrounded by jackets, in segments, which enables the barrel to be temperature controlled using either water, steam or oil as extrudate crosses specific processing zones. Thermostatically controlled electric heaters surrounding the extruder barrel can also be used to control the processes temperature along the length of the barrel.

4. Extruder Screw - Single screw extruder can be analysed in three sections.

Feed zone - The section is characterised by its deep flights which easily accept the feed material as it is fed into the extruder. The feed zone is generally 10 - 25% of the total screw length and continually works the feed material into a continuous mass expelling the air voids as it transports the feed material to the transition zone (Harper, 1981).

Transition, kneading or compression zone - Characterised by either decreasing flight heights, reducing flight pitch or internal restrictions that cause compression of the material. The screw design increases shear rate and mechanical energy working on the material causing an increase in temperature (Harper, 1981).

Metering or cooking zone - The metering section of the screw has shallow flights and controls the extrusion rate, accounts for the majority of the power consumption and causes the uniform pressure which occurs behind the die (Harper, 1981). Viscous dissipation of mechanical energy is typically large in the metering section so that the temperature increases rapidly.

5. Extruder Discharge - The die restricts product flow, thereby increasing the residence time causing the extruder to develop the required pressure (Harper, 1981).

Residence time of a food product passing through the extruder is a function of the design of the screw and its speed of rotation. Typically the residence time is between 60 and 270 seconds, discharge temperatures can be in excess of 200°C. Boiling or flashing of the extrudate does not occur due to the high pressures within the barrel, typically between 40 and 60 atm (Harper, 1978).

The rapid release of pressure, that occurs as the extrudate passes through the die, causes an expansion of the product when the extrusion temperature exceeds the normal boiling point of water, this is because the superheated water flashes instantly with the reduction of pressure (Harper, 1978)

3.7.3 Classification of Extruders

Rossen and Miller (1973) (cited in Badrie, 1990) classified extruders in three ways:-

- on general functional characteristics;
 1. *Pasta extruders* - used for low pressure applications.
 2. *High-pressure forming extruders* - used for compressing and shaping pregelatinised dough feed into products which normally require further processing.
 3. *Low shear cooking extruder* - used for soft-moist pet foods or high moisture food products. Characteristics are moderate shear, high compression to enhance mixing, and grooved barrels to prevent slip at the barrel wall. Heat can be applied to the barrel or screw. Little viscous dissipation of mechanical energy occurs due to the relatively low viscosity of the material being extruded.

4. *Collet extruder* - relatively dry feed materials heated rapidly to temperatures in excess of 175°C, so that starches can be gelatinised and dextrinised. High temperature causes violent flashing of moisture, creating a puffed dry product. Rapid viscous dissipation of the mechanical energy input to the short screw (L/D - 3:1) occurs because of the relatively high shear in the shallow flights of the screw operating in a grooved barrel.
5. *High-shear cooking extruder* - similar to collet but has longer residence time with excess heat removed by cooling the barrel.

- on thermodynamic considerations;

1. *Autogenous* - entire heat input to the process comes from dissipation of mechanical energy inputs and little or no heat is removed from the barrel.
2. *Isothermal* - constant temperature maintained throughout the length of the barrel.
3. *Polytropic* - Cookers which have jacketed barrels where heat is alternatively added or extracted. Operate in the polytropic regime.

- by the manner in which pressure is produced.

1. *Direct or Positive Displacement Type* - includes ram or piston type and intermeshing twin-screw. The extruded product from a ram or piston type are essentially unchanged from those of the feed material. The intermeshing screw type can however be high shear and therefore modify the characteristics of the extruded product.
2. *Indirect or Viscous Drag Extruder* - modifies the characteristics of the extruded product due to the viscous drag developed. These include single-screw extruders and non-inter-meshing multiple-screw extruders.

Hauck (1981) (cited in Badrie, 1990) categorised extrusion cookers as low, medium or high shear illustrated in Table 3.3.

Table 3.3 *Extruder Classification*

	Low Shear	Medium Shear	High Shear
Product moisture, %	25-75	15-30	5-8
Product density, g/l	320-800	160-510	32-200
Max. barrel temp., °C	20-65	55-145	110-180
Max. barrel pressure, kg/cm²	6-63	21-42	42-84
Screw speed, rpm	100	200	200
Parallel flow channels, n	1	2	2 or 3
Ds/h *	3.0-5.3	5.0-8.5	8.0-18.0
Energy conversion, kW/kg	0.01-0.04	0.02-0.08	0.10-0.16
Typical products	Pasta products Meat products Gums	Textured soy Expanded and semi-moist pet foods	Breakfast cereals Thin boiling starch

* screw diameter / channel depth

Source: Hauck. (1981).(cited in Badrie, 1990)

3.7.4 Extrusion in oilseed processing

In the early 1960's the V.D. Anderson company began experimenting with extrusion as a preparation treatment for raw rice bran prior to oil extraction with solvents. Rice bran deteriorates rapidly upon the removal of the bran from the rice kernel. The deterioration is due to the action of the enzyme lipase which causes the break up of the rice oil into free fatty acid.

Traditional heat treatments of the rice bran slowed down, but did not eliminate, the action of the enzymes. It was discovered that processing raw rice bran in an extruder destroyed the activity of the lipase resulting in a product stable against the rise of free fatty acid. It was also discovered, for solvent extraction of the oil, the extruded rice bran had improved percolation characteristics over raw rice bran due to the larger particle size and increased porosity of the extrudate (Williams, 1989).

In 1966 V.D. Anderson Company was issued with a patent for the extrusion process as a preparation treatment for rice bran (U.S. Patent, 1966). Two major needs in the industry were made achievable with the use of extruders, firstly, enzyme denaturing and secondly, the reduction of processing costs, especially in the energy short countries of South America. These factors hastened their adoption within the industry (Lusas *et al.*, 1990).

The denaturing of undesirable enzymes is also important in the processing of oilseeds other than rice bran, these include phospholipase in soybean (Lusas *et al.* 1988) and myrosinase in rape seed (Carr, 1990).

Extrusion techniques for the processing of soybeans and cottonseeds were developed in Brazil and introduced to the USA in the late 1970's (Williams, 1989). By 1990 Lusas *et al.* (1990) estimated that extruders were employed in approximately 60% of the soybean and cottonseed tonnage being processed in the USA.

A number of articles have been published identifying the advantages of introducing extrusion into the preparation of oilseeds for solvent extraction.

Farnsworth *et al.* (1986) looked to substantiate the claims of Latin American soybean processors that extrusion preparation vastly improved the extraction process, nearly doubling the capacity of solvent extraction plants whilst improving oil and meal quality.

An experiment was designed to compare the extraction efficiency for soybean and cottonseed using traditional flaking preparation treatments against using extrusion as the preparation process.

The results of the experiment determined that cottonseed and soybean extruded at moisture contents below 12%, with screw speeds ranging between 150 and 300 revs/min and die exit temperatures between 90 and 110°C did extract better than traditional flakes. The collets had a high bulk density and low solvent hold thereby increasing the capacity of the extractor and reducing energy cost for desolventisation. No improvement in meal quality was found by extruding and it is possible that the oil produced may require more refining.

A commercial assessment of the benefits of incorporating extruders in the oil processing operation was also carried out by Farnsworth *et al.* (1986). The factors included in the study were the increased extractor capacity due to increased bulk density and energy savings due to the increased efficiency of desolventisation following extrusion. The increase in average revenues for various capacity plants was stated as \$0.22/t representing a pay back of less than 1 year.

Watkins *et al.* (1989) also studied the effects of extrusion in the preparation of soybean and cottonseed. The findings of increased bulk density of extrudate, 50% greater than flaked material, and much reduced solvent use, due to the porous collets produced from the extruder resulting in less solvent hold up and increased efficiency in desolventisation, is reiterated. They reported that the use of extrusion in the preparation of oilseeds increases extraction plant capacity by 50% with little capital expenditure.

Microscopy work carried out by Watkins *et al.* (1989) show how extrusion cooking increases the oil availability by releasing and coalescing oil from the oilseeds. At a magnification of $\times 50$ and a fat stain of Sudan IV, cottonseed flakes show tiny red spheres of oil, with extruded cottonseeds at the same magnification and stain, the oil can be clearly seen to have collected in much larger pools.

Aguilera *et al.* (1986) carried out a laboratory scaled experiment to see the effect of using extrusion as a preparation of high-oil corn for solvent extraction of oil. Three preparations were compared in the experiment, these were flaking, conventional extrusion and steam-injection extrusion. The corn was split into two samples and conditioned to 15 and 20 % moisture content. Both samples were ground in a mill, sieved in a 20 mesh screen, tempered to 80°C and rolled into flakes at roll gaps of 0.25 and 0.5 mm. Extruded samples were prepared in a Wenger X-5 laboratory extruder at moisture content 10.2-12.7 %, die size of 0.4 mm, and exit temperature 75-85 °C. Steam was injected towards the front of the barrel.

The results from the experiment revealed that conventionally extruded samples had almost twice the concentration of oil in the miscella as flakes. These results are consistent with data presented for soybeans by Rittener (1984) who suggests that rupturing of spherosomes by extrusion is 30% more effective than by flaking. Less than 40 % of the oil was extracted in the steam-injection extruded samples. It was evident that the steam injection gelatinised the starch in the corn. The degraded starch traps the lipids resulting in cells impermeable to solvents in conventional extraction plants.

Expanders have also been used in the preparation of high oil content oilseeds including sunflower and rapeseed.

Buhr (1990), of CSP Foods Ltd., Altona Manitoba, Canada, reported that the introduction of extruders into their processing lines, following the prepress, for sunflower and canola has improved the plant throughput and reduced operating costs. A number of benefits to the pre-press operation and the extraction plant have been reported following the introduction of extruders. The benefits to the pre-press operation stated by the author include a reduction in wear to the press cage and shaft because of the lower pressing pressures required for the process, the quality of cake produced less critical and a reduction in manpower due to significantly less attention needed to monitor cake production.

The benefits to the extraction plant included an increase in extractor capacity of 70-80%, improved drainage of miscella from the cake, less fines in the extractor (Lajara (1990) states that the incorporation of fines within the expanded material improves percolation in the extractor), a reduction in solvent use, lower energy consumption in solvent recovery and a lower residual oil in meal. Lusas *et al.* (1988) state that with the introduction of an extruder in to a direct solvent extraction plant the residual oil in dried meal can be reduced from 1% to 0.5%.

In the early 1990's Anderson International experimented with the use of drained extruders as a preparation for high oil content seeds. Some success was achieved with the system on sunflower and groundnut, however, by their own admissions their systems were susceptible to variations in preparation conditions with the highest standards of preparation needed for adequate performance (De Smet Rosedowns Ltd., 1994).

Pedrotti *et al.* (1997) has however since written that extruder technology is now being adopted for the preparation of high fat oilseeds giving sunflower as an example. For this process a drainage cage mounted just before the discharge end of the extruder is required to enable a percentage of the oil to be expelled before reaching the discharge.

The system also requires the means to control the internal pressure of the extruder to enable the optimum drainage pressure to be maintained. The extrusion material can be more successfully expanded once the oil content has been reduced. The drained extruders are installed immediately after the flaking mills eliminating the need for a pre-press. Pedrotti *et al.* (1997) state a reduction in oil content for sunflower seed from 42-44% to 28% following processing in a drained extruder.

The objectives of using extrusion in the processing of oils is to heat the seed to denature the protein and to make the cell walls and contents sufficiently brittle so that oil will be freed from the spherosomes by the shearing action. The general guidelines for operating conditions for extrusion given by Lusas *et al.* (1988) are 10 - 15% moisture and a final product temperature of 100 - 120 °F. Up to 5 % moisture content can be flashed off when the processed seed leaves the extruder die and a further loss occurs during the cooling of the collets before further processing.

In summary a list of the reported advantages of introducing an extruder into the preparation of oilseed for solvent extraction is given.

1. Increased recovery of oil - Lusas *et al.*, (1988) and Buhr (1990).
2. Coalescing of oil - Watkins *et al.*, (1989).
3. Rupturing of oil cells - Rittner, (1984).
4. Increased capacity of solvent extractor - Farnsworth *et al.* (1986), Lusas *et al.*, (1988), Watkins *et al.*, (1989), Buhr, (1990), Mag, (1994) and Pedrotti *et al.* (1997).
5. Increased capacity of conveyors etc., because of higher density of higher density of extruded material versus flakes. Lajara, (1990).
6. Improved percolation Williams, (1989), Lusas *et al.*, (1988), Lajara, (1990) and (Mag, 1994).
7. Reduction in solvent hold up Farnsworth *et al.* (1986) and Watkins *et al.*, (1989).
8. Reduction in solvent use Watkins *et al.*, (1989).
9. Reduction in energy requirements for solvent recovery. Farnsworth *et al.* (1986), Lusas *et al.*, (1988), Williams, (1989), Watkins *et al.*, (1989) and Buhr (1990).
10. Denaturing of undesirable enzymes. Williams, (1989) and Lusas *et al.*, (1988)

Wang *et al.* (1995) reported on a study to explore the suitability of using a single screw extruder to extrude canola paste directly into a CO₂ supercritical extractor. The benefits of using extrusion in the preparation of oilseeds for traditional solvent extraction would be equally beneficial to a SCFE process. Extrusion would also have the added benefit of being able to deliver the canola at the elevated pressures required in SCFE. The study did find that the custom built extruder was able to achieve discharge pressures of 30 MPa which indicates that extruders are suitable feeders for extractors using SC-CO.

Nelson *et al.* (1987) reported on the development of using dry extrusion as an aid to mechanical expelling of oil from soybeans. In a pilot scale experiment coarsely ground soybeans, at a moisture content of 10 - 14% was extruded at approximately 135 °C with a dwell time of 25-30 seconds. Extrudate emerging at the die in a semi-fluid state was immediately fed into a screw press. At these condition a 70% oil recovery was achieved after a single press.

The authors of the paper suggest that a higher oil recovery rate could be expected, firstly, by directly coupling the extruder to the press eliminating heat loss from the extrudate, and secondly, by operating under commercial conditions using more efficient presses compared to the small scale pilot type presses used in the experiments.

The pressed oil had a stability comparable to that of refined deoderised oil according to the National Soybean Producers Association (NSPA) specification.

Said (1998) reported that The Instra-Pro Division of Triple "F" Inc. of Des Moines, Iowa has recently commercialised the process described by Nelson *et. al* (1987). The process was initially focused on soybeans however has since been used on other seeds. Cottonseed has been commercially extruded and expelled producing a residual oil of 5-7%. The process has also been used on sunflower seed in Russia, Latvia and Lithuania.

3.8 Potential for use of extrusion in the preparation of rapeseed for mechanical oil extraction

The conditions that the food material is subjected to within the food extruder are comparable to the variety of conditions oilseed rape is subjected to in the traditional oilseed preparation process described earlier in the report. The rotating screw within the stationary barrel applies a continuous shear action to the food material while the heating jackets around the barrel, and heat produced through mechanical energy, cook the ingredient.

Many of the advantages of a single screw extruder that makes it favourable in the food processing industry over traditional processes could also be equally advantageous to the oil processing industry as a preparation treatment for the mechanical extraction of high oil content oilseed. Advantages include:

- Machine versatility - Temperature, pressure and shear applied to the feed material can be accurately controlled to produce optimum processing conditions.
- High productivity - Conditioning time of the rapeseed could be greatly reduced due to the much quicker cooking period within the extruder. A conventional stack cooker will take between 45 minutes to an hour to heat the seed to the required temperature. This temperature could be reached in a matter of seconds in an extruder. Extrusion is a continuous processing system that could possibly feed conditioned oilseed directly into a screw press.
- Low cost - An extruder taking unconditioned oilseed, conditioning the oilseed and feeding the conditioned meal directly into a screw press would greatly reduce the floor space requirement compared to traditional processing equipment, i.e. roller / flaking machines, stack cookers and conveyors. Labour requirements would also be reduced with a single oilseed preparation process.
- High product quality - Extruders are capable of high temperature processing with short residence time termed as HTST. HTST processing minimises degradation of food nutrients by heat and is capable of destroying most of the undesirable enzyme systems including lipase and myrosinase, and micro-organisms in food (Harper, 1981).
- Energy efficient - Extrusion is an energy efficient process for shearing and cooking feed mixture.

A number of the characteristics of extrudate identified as being advantageous in the preparation of oilseeds for the solvent extraction of oil could also prove to be of benefit in the preparation of oilseed for the mechanical extraction of oil. The advantages include:

- Coalescing of oil within the extrudate making the oil more readily available for expelling.
- Porous collets aiding in the drainage of oil from the solids, especially in the early stages of pressing prior to the press material becoming densely packed by the high internal pressures exerted on the press material from the positive compression ratio along the press shaft.
- Greater efficiency in the rupturing of oil cells compared with conventional flaking, enhancing the oil availability at the pressing stage of the extraction process.
- The increased density of extruded rapeseed over flaked seed will increase conveyor capacity and possibly the screw press capacity which will reduce process operational costs.
- The rapid denaturing of undesirable enzymes with a HTST process.

Extruding oilseed as a preparation treatment for mechanical extraction could meet the criteria, proposed by Mrema *et al.* (1984), as a process applying undrained loading to the oilseed to rupture their cell walls in turn enhancing the performance of the screw press. The processing condition described by Mrema *et al.* (1984) is comparable to the environment within the transition and metering zones of a single screw extruder.

The throughput of a screw press would also likely to be improved subsequent to oilseed being conditioned in an extruder. The expanded extruded collets being fed in to a press should provide a good aggregate for the screw to grip, reducing material rotation and improving the drag flow efficiency.

The study of published literature revealed that there is need within the vegetable oil processing industry to improve on the current oilseed preparation and extraction processes. The study suggests that the introduction of extrusion technology to the oil processing industry as a replacement preparation process for the current flaking and conditioning processes, could possibly improve the efficiency of the pressing process resulting in greater oil yields from the mechanical oil extraction process. The substitution of flaking rolls and conditioner with an extruder could also increase the throughput of the preparation process and reduce investment and energy costs attributed to the preparation of oilseeds.

The findings from the literature indicated that a practical investigation of the potential of extrusion technology as a preparation treatment worth pursuing. It was therefore decided that a practical study should be planned and carried out to investigate the full potential of extrusion as a preparation treatment, identifying the optimum process conditions for the extrusion process, and comparing it with traditional flaking and conditioning processes. The analysis was to be considered on the basis of production efficiency and commercial gains.

4. METHODOLOGY

4.1 Introduction

A set of experiments were planned to assess the possibility of introducing extrusion as an alternative to traditional preparation treatments to improve the efficiency of mechanically extracting oil from rapeseed.

This chapter discusses the experimental plan set to identify the optimum extrusion variables and seed moisture content to maximise the efficiency of the preparation and mechanical oil extraction process for rapeseed. The chapter will also detail the procedures used throughout the research for analysing residual oil contents, moisture content, the degree of preparation calculated from a milling defect analysis and the effect of the preparation treatment on the microstructure of the seed.

4.2 Experimental plan

The experimental procedure of the research is divided into two major sections. Firstly, a set of laboratory scale extrusion experiments where a number of extruder operating conditions and material moisture contents are assessed to determine the processing variables or combination of variables that are significant to the preparation process, and to ascertain at what range the variables most enhance the oil extraction process. The effectiveness of the preparation treatments to enhance the mechanical oil extraction process is determined using a small laboratory ram press.

The second set of extrusion experiments are with a larger scale extruder. The trials will permit larger processing runs to closer simulate that of a commercial processing plant enabling a more realistic assessment to be made on the viability of extrusion as an alternative preparation treatment. For this set of experiments a screw press is used to determine the effectiveness of the preparation treatments in enhancing mechanical oil extraction.

The process variables used in the initial experimentation and the range within each variable are discussed in the following sections.

4.2.1 Moisture content

Literature from various sources have identified the moisture content of oilseeds as a major variable determining the efficiency of an oil extraction process. Work from Singh *et al.* (1984), Stein (1984), Vaughen (1970), Vivek *et al.* (1988), Fasina *et al.* (1989), Ajibola *et al.* (1990 and 1993), Leslie *et al.* (1974) and Niewiadomski (1990) discussing the importance of this variable in the extraction of oil from various oilseeds have previously been identified in the literature review in sections 3.4.1 and 3.4.3.

Problems of moisture content of oilseed lower than 10% speeding up the hydrolysis of glucosides during heating should be eliminated with the HTST conditioning provided with the extrusion process. This should also be the case with low moisture content hindering the destruction of enzyme systems such as myrosinase.

De Smet Rosedowns Ltd. recommend that rapeseed is pressed at approximately 4% moisture content to achieve the maximum performance from their presses. If the moisture content is too high a problem with emulsification of the crude oil can occur.

The oilseed moisture contents in the experimentation range from 2% to 10%. It should be noted that during the extrusion process it is considered that the moisture content of the oilseed will be reduced by about 2% to 4% depending on operating conditions.

4.2.2 Temperature

The temperature to which oilseed is heated in a commercial stack cooker is 70°C to 100 °C. This is the minimum temperature that an oilseed needs to be heated to destroy undesirable enzyme systems and micro-organisms. For this reason, the lowest temperature variable chosen for the initial experiments is 80°C.

Section 3.4.1 discusses other benefits of cooking the oilseed prior to oil extraction which include coalescing small oil droplets into larger ones, lowering oil viscosity and arguably, rupturing oil cells. The use of an extruder gives the opportunity to heat the oilseed to far greater temperatures than traditional processes and it will be interesting to see the effect this has on the process. It has therefore been decided to take the upper limit of the temperature variables near to the maximum of the extruder capability at 180°C.

It is possible that oxidation of the extrudate may occur on entering atmospheric conditions at high temperatures. If this is the case, blanketing the extrudate with an inert gas to eliminate problem has been considered.

4.2.3 Compression ratio

High compression ratios (in the order 10:1) used in high pressure screw pressing are not required within an extruder. No drainage occurs within an extruder, therefore no oil loss will occur during the process. The volume of the oilseed is only being reduced by the volume of voids being expelled and moisture steaming off in the feed zone.

Compression within the extruder barrel is used to enhance shear within the bulk rather than mixing which can occur with excessive void space.

Another reason for not subjecting the oilseed to extreme radial pressures, resulting from a high compression ratio, is it is not the objective to squeeze oil from the seed at this stage but to make it freely available for a future process.

An alternative to the last argument is that if Mrema *et al.* (1984) criteria for cell rupture i.e. applying undrained loading to the oilseed, is to be achieved, the radial pressure exerted to the oilseed by a high compression ratio may be necessary.

With the above arguments in mind, it is considered that the screw compression ratios of ranging from 1:1 to 5:1 are to be assessed.

4.2.4 Die size

The die size used at the extruder discharge will effect the pressure build up in the metering zone which in turn could effect the efficiency of cell wall rupture, the throughput of the machine and the expansion rate of the extrudate. The die sizes to be used for the experiment range from 3mm to 7mm.

4.2.5 Screw speed

The screw speed will also effect pressure build up within the extruder barrel and machine throughput as well as the shear efficiency. Screw speeds ranging from 80 to 180 rev./min. (maximum extruder capability) are to be used in the experiment.

4.3 Quality assurance and control

Quality assurance management involved maintaining high levels of diligence in preparing, handling, processing and analysing samples to minimise the levels of cross contamination between samples or by other materials. All equipment used during the experimental process was thoroughly cleaned between individual experiment runs and samples were sealed in containers, indelibly labelled and stored. Experimental and analysis procedure methodologies were identified or developed and followed precisely to ensure consistency throughout the research.

4.4 Analysis procedure

The procedures for analysing residual oil content, moisture content, material microstructures, and the milling defect used throughout the period of research are detailed in the following sections.

4.4.1 Residual oil analysis

4.4.1.1 PerCon Inframatic 8100 Near Infrared Analyser

The analysis of the residual oil in extrudate and press cake was carried out using an PerCon Inframatic 8100 analyser. The Inframatic uses near infrared reflection (NIR.) to analyse oil and moisture content. The NIR method of analysis has been adopted as the standard test method for the determination of protein and oil in grain and oilseeds in a number of countries and is accepted as such by the A.A.C.C (American Association of Cereal Chemists) and the F.G.I.S. (Federal Grain Inspection Service USA).

Residual oil content can be measured far more rapidly with an NIR. analyser, compared with traditional soxhlet extraction with hexane, taking approximately 20 seconds to analyse a ground sample as opposed to at least 6 hours with a soxhlet. NIR. is however an indirect form of analysis and requires the use of established standard methods of analysis, in the case of oil analysis of rape seed the soxhlet, as a reference.

NIR analysis uses light in the near infrared region between 1400 and 2400 nano-meters. The Inframatic 8100 uses a tungsten light source which is passed through six narrow band-pass interference filters producing single wavelengths of light. The single wavelengths of light are irradiated into the sample through a quartz window. Individual constituents within the sample absorb energy at specific wavelengths and it is the light diffusely reflected from the sample that carries the information as to the energy absorbed at the specific wavelengths. The amount of a given substance in the sample will be proportional to the amount of light absorbed by the sample at given wavelengths. The percentage of the individual components present within the sample is automatically calculated by a built in micro-processor in the Inaframatic. The actual calculation used is shown below:

$$L = \log \frac{\text{Reflection of Standard}}{\text{Reflection of Sample}}$$

L is calculated for each filter and is used in the following calculation.

$$\% = C0 + (C1 * L1 + C2 * L2 \dots + C7 * L7) * C8$$

C0 = Bias factor specific for the parameter under investigation

C1 ... C7 = Filter constants for particular wavelengths

L1 ... L7 = Reflection (log) value for the different wavelengths

C8 = Slope value of the regression curve

The inframatic requires the sample to be analysed to be ground to a 0.8 mm particle size. The analyser is susceptible to inconsistent results with uneven particle size. A standardised sample preparation procedure, detailed below, was adopted to ensure consistency within the analysis.

Sample preparation

1. Grind a 40 g sample in a coffee grinder for 25 seconds.
2. Pack approximately 15g of the ground sample into the sample chamber on the analyser using a spring loaded plunger.
3. Following analysis empty the chamber brushing away any remaining sample and clean the optical window with a soft cloth moistened with alcohol to remove any oil before the next sample.

The Inframatic 8100 takes 10 readings from each sample and calculates their average to give a final result.

To ensure the validity of the results obtained from the NIR. analyser the results were subjected to a correction factor calculated against results from a soxhlet extraction with hexane.

4.4.1.2 Soxhlet method of analysis

A standard soxhlet extraction with hexane in accordance to BS 4289 : Part 4 (1989) was used to calculate the correction factor and regularly check the accuracy of the Inframatic analyser.

Four samples of rapeseed, at different stages of processing to give a range of residual oil contents, were analysed using the soxhlet and Inframatic. The sample analyses was replicated 3 times and averaged. The results of the analysis were plotted on a graph shown in figure 4.1 and the correction factor for the Inframatic calculated.

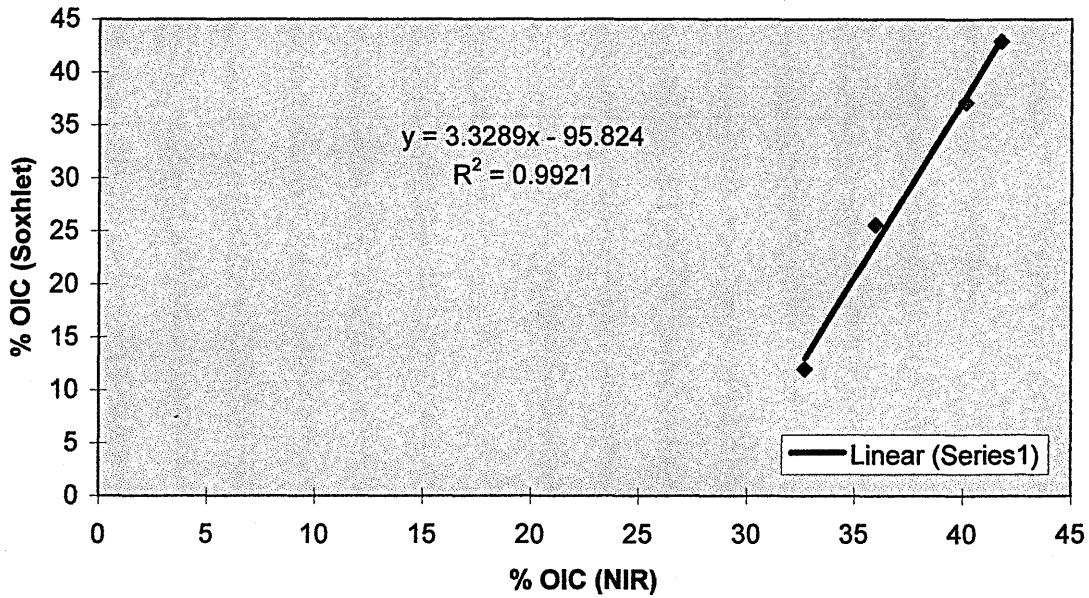


Figure 4.1 A graph showing the results of the analysis of the % OIC, of four different samples, given by the Inframatic NIR analyser against those calculated from a soxhlet extraction with hexane.

Figure 4.1 shows a good linear correlation between the results obtained from the inframatic against those from the soxhlet. It was therefore considered that it was acceptable to use the oil analysis results from the Inframatic corrected with the correction factor $y = 3.3289x - 95.824$, calculated in figure 4.1, as the method of oil analysis throughout the research.

4.4.1.3 Independent analysis

An independent analysis of residual oil was also carried out to assess the accuracy of the analysis procedures being implemented. The independent analysis was carried out by Beverley Analytical Laboratories, (BAL) Hull Bridge Mills, Tickton, Beverley, East Yorkshire, UK. Figure 4.2 shows the comparison between the % OIC results from the independent analysis and those from the corrected NIR analysis for a range of oil cake samples.

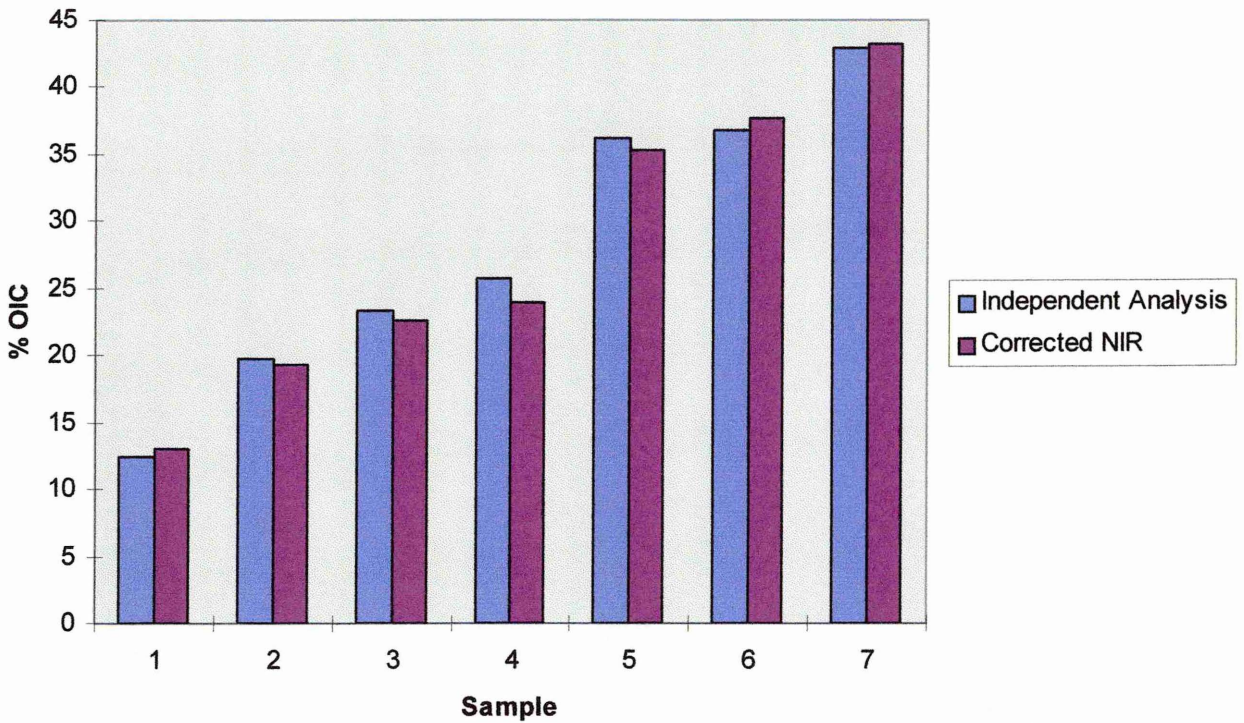


Figure 4.2 A chart showing the comparison between the analysis of % OIC on a range of oil cake samples carried out by BAL compared to those calculated from the Inframatic NIR analyse

It can be seen from figure 4.2 that the two methods of analysing the % OIC give very similar results. In all but sample 4 the results from the two methods of analysis gave the % OIC within ± 1 % of each other. The results from figure 4.2 confirmed that the use of the NIR analyser for the analysis of residual oil was acceptable.

4.4.2 Moisture content

The analysis of moisture and volatile matter content of rapeseed, extruded rape seed and press cake was determined in accordance with BS 4289: Part 3: 1978. British standard methods for the analysis of oilseeds. Part 3. Determination of moisture and volatile matter content.

4.4.3 Microscopy

Light microscopy is considered an important tool for the analysis and understanding of the effectiveness of extrusion for the preparation of rapeseed for oil extraction with a press. An examination of the rapeseed microstructure following extrusion at various process conditions permits an assessment of how individual process variables, or combinations of process variables, effects the cell structure of the seed during the preparation treatment.

A microstructure analysis enables the extent of seed structural disturbance and oil cell rupturing at different process conditions to be assessed and compared. The analysis procedure enhances the understanding of how the microstructure of a prepared rapeseed effects the efficiency of the subsequent oil extraction by pressing.

4.4.3.1 Sample preparation procedure

A standard botanical histology procedure was used to prepare the rapeseed sample for analysis of the microstructure with light microscopy. The stages of sample preparation required for botanical histology, as for animal histology, are fixation, dehydration and clearing, embedding, sectioning and staining. The procedure applied for each of the preparation stages for the analysis of the extruded rape samples are detailed below.

1. Fixation

A Formalin: Acetic: Alcohol (FAA) mixture was used as a fixative. The following concentrations for the FAA. are listed below:

70% Alcohol	90%
Glacial acetic acid	5%
Formalin	5%

The mixture is made up immediately before use. The samples remain in the fixative for at least 1 week before the next preparation stage.

2. Dehydration, clearing and infiltration

An alcohol - toluene - molten wax sequence was used for the dehydration and clearing stages of the sample preparation. The chemical concentration and sequence schedule for the process is detailed below.

80% alcohol	3 hours
100% alcohol	3 hours
100% alcohol	3 hours (can be prolonged overnight)
Toluene	3 hours
Toluene	3 hours
Toluene	3 hours (can be prolonged overnight)
Wax	3 hours
Wax	3 hours
Wax	3 hours

3. Embedding and mounting block

Following the infiltration with wax the sample is cast in a block of wax. A mould is filled with molten wax and the sample placed in to the mould. The sample is orientated so that the side to be cut is at the bottom of the mould. The wax is allowed to cool until a fairly thick skin is formed on the mould surface. The mould is then lowered in to cold water and left until the wax is cold. If the wax is allowed to cool at room temperature there is a risk of wax crystals forming.

When the wax is hardened the embedded sample is removed from the mould and any surplus wax trimmed off the sides of the blocks. The blocks are cut in to a trapezium shape and mounted on to a wooden block. To attach the wax block to the wooden block, a heated spatula is held on the wood, the wax block is placed on the spatula and the spatula removed. The molten pool of wax, produced by the heated spatula, solidifies welding the wax block to the wood.

4. Sectioning

The sample, mounted on the wooden block, is clamped in a microtome and sectioned. The section thickness for the rape samples are cut to 10 μm . The sectioned samples are attached to slides by a very thin coat of glycerol - albumen adhesive.

5. Staining

The sections are stained in safranin and fast green. Before staining the sections must be de-waxed in toluene and hydrated by passing them through a series of alcohols. Following staining the samples are dehydrated by passing them through a series of alcohols, cleared in toluene and mounted in a synthetic (D.P.X.) The chemical concentration and sequence schedule for the process is detailed below.

Stain solutions

Aqueous Safranin	Safranin O (water soluble)	1 gm
	Distilled water	100 ml

Fast Green	Fast green F.C.F	0.2 gm
	95% alcohol	100 ml

Toluene 10 minutes

Toluene 10 minutes

100% alcohol 10 minutes

100% alcohol 10 minutes

90% alcohol 10 minutes

70% alcohol 10 minutes

50% alcohol 10 minutes

Distilled water 10 minutes

Safranin 30 minutes

Wash quickly in tap water to remove excess stain

Dehydrate quickly in 50% then 70% alcohol

Fast green 5 -10 seconds

Dehydrate quickly in 50%, 70% then 100% alcohol

Toluene 10 minutes

Toluene 10 minutes

Mounted in a synthetic (D.P.X.)

The samples are then viewed under a microscope and photographed to produce a hard copy for the analysis.

4.4.4 Milling defect

Milling defect is an analysis procedure used to give an indication of the efficiency of the preparation treatment in terms of oil availability for oil extraction. This analysis procedure was a useful tool in this research for two purposes. Firstly, the milling defect offers an alternative means to assess the performance of the preparation treatment which, when used in conjunction with the residual oil and microstructure analysis, provides a comprehensive assessment of the preparation process. Secondly, as the milling defect analysis is carried out prior to pressing, the procedure enables a direct comparison to be made between the oil availability following the preparation treatments being evaluated in this research and those currently being used commercially without the necessity of standardised pressing conditions.

The procedure to determine the milling defect is described below.

1. Perform a 3 hour soxhlet extraction with hexane as the solvent on the prepared material. Evaporate the solvent and dry to a constant weight (WA).
2. Desolventise the extractor cartridge and finely grind the contents in a laboratory mill.
3. Put the resultant meal back in the same extraction cartridge.
4. Repeat the extraction for another 3 hours on a different flask and proceed as in 1 (WB).

The milling defect (MD) is the oil content in % of the second extraction on a dry weight basis, expressed against the total sample weight with the oil from the first extraction having been deducted.

$$MD = \frac{WB}{\text{Original Sample} - WA} \%$$

The milling defect was calculated independently by Beverley Analytical Laboratories, Tickton, Yorkshire, UK.

De Smet Rosedowns Ltd. state that a milling defect value of between 3 and 5 would be expected from a prepared sample in a commercial processing plant. A milling defect value above 5 would reduce the performance of an extraction process. A preparation treatment should aim to achieve as low a milling defect value as possible if the maximum performance from an extraction process is to be achieved.

5. LABORATORY SCALE EXTRUSION EXPERIMENTS

5.1 Introduction

The set of laboratory scale experiments designed to determine the processing variables or combination of variables that are significant to the preparation process, and to ascertain at what range the variables most enhance the oil extraction process are described and discussed within this chapter. The aims, objectives and methodology of the set of experiments are detailed along with a description of the equipment used. The results and of each experiment is presented, analysed and discussed in detail at the end of the chapter.

5.2 Aim

To determine the optimum operating conditions of a small scale laboratory extrusion cooker as a preparation treatment prior to the mechanical extraction of oil from rapeseed, and, compare this process with traditional preparation treatments. The effect that individual extruder operating variables and moisture contents of the material have on the preparation process are also to be assessed.

5.3 Objectives

- Design and implement a set of experiments using an extrusion cooker to obtain a number of samples from a range of operating variables and material moisture contents.
- Record power requirement, oil extraction efficiency and throughput for each operating condition and study the effect the preparation treatment has on the microstructure of the rape seed.
- Analyse the results to determine the optimum material moisture content and extruder operating conditions as a preparation for the efficient extraction of rapeseed oil and assess the effect individual operating variables have on this process.

5.4 Methodology

- Design a set of experiments to enable the full range of each operating variable and material moisture contents to be assessed.
- Design and manufacture a ram press to enable a standard oil extractability test to be carried out on each of the extruded samples obtained from the experiment.
- Conduct the experiments to obtain extruded samples and record required operating data, and then press the extrudate in the pressure cell to assess the oil extractability.
- Analyse the results of the experiment to determine the optimum operating conditions and the effect the individual variables have on the process. Compare the performance of the extruder as a preparation process with the traditional preparation process.

5.5 Equipment

5.5.1 Extruder

5.5.1.1 *Extruder specification*

The extruder used for the set of experiments was a Brabender laboratory single-screw cooker-extruder powered with a 2.2 kW electric motor.

The extruder barrel is fluted to prevent the feed material rotating with the screw during the extrusion process. As with screw pressing, rotational slippage of the material within the barrel increases the residence time of the material being extruded, in turn reducing the throughput of the machine. Excessive rotational slippage can stop throughput completely. The barrel is insulated along its length and can be heated in the final third of the barrel length with electric heaters. The barrel can also be cooled by circulating compressed air around the barrel.

The extruder screws available with the extruder are a chromed continuous screw type, 19 mm in diameter and with a screw length of 400 mm. A range of screw compression ratios are available with the machine.

A picture of the Brabender extruder used for the experiment is shown in Figure 5.1.

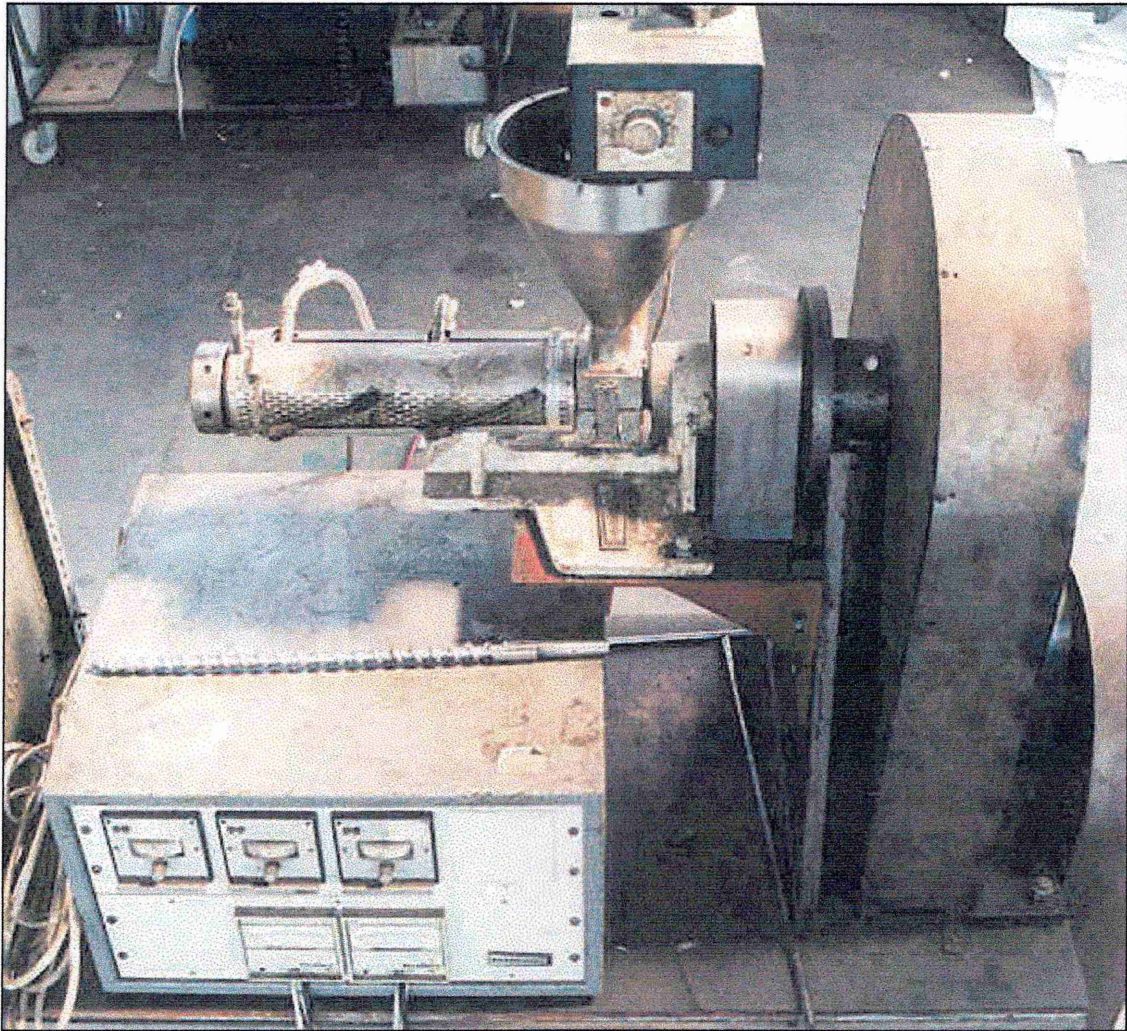


Figure 5.1 *Brabender extruder used in the set of laboratory scale extrusion experiments*

The extrusion operating variables for the Brabender detailed below.

Compression ratio	1:1, 2:1, 3:1, 4:1 and 5:1
Operating Temperatures	maximum 200°C (variable)
Die size	1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm and 7 mm
Screw speed	20 - 200 rev/min (variable speed)
Operating Pressures	(adjusted using die size and worm speed)
Shear	(adjusted using die size and worm speed)
Residence time	(adjusted using die size and worm speed)

5.5.1.2 Extruder operation

A number of pilot trials were completed prior to the main set of experimentation. The first reason for the pilot trials was to ensure that the Brabender extruder was suitable for extruding rapeseed. The second reason was to identify the range of each individual operational variable that would enable the extruder to operate consistently at a reasonable throughput and produce a satisfactory product. This needed to be carried out before deciding on the range of operating variables to be used in the set of experiments. The major findings from the pilot trials are highlighted below.

- Oil Logging - initial trials highlighted a problem of oil logging after only a few minutes of operation. Oil logging reduces the axial movement of the feed material, in turn reducing the throughput of the extruder. The pressure gradient within the extruder barrel forced the free oil, against the flow of the solid material, towards the feed end of the extruder and eventually up into the feed hopper. The oil logging made the throughput of extruder inconsistent and eventually, depending on operational variables, stopped throughput completely.

In the initial stages of the research it was considered that the environment within the transition and metering zones of the extruder, during the extrusion process, could possibly meet the criteria proposed by Mrema *et al.* (1984) as a process applying undrained loading to the oilseed to rupture their cell walls. However, following the problems encountered with oil logging, it was considered that an oil drain at the feed end of the extruder was required to remove the free oil from barrel.

A combination of a drilling behind the material inlet to drain away the free oil, together with a positive feed screw auger fitted to the feed hopper, eliminated the oil logging problem.

- Temperature - when extruding rapeseed it was noted that the machine operates at between 70°C and 80°C due to frictional heating alone with no additional heating from the heaters. With air cooling the minimum constant operating temperature achieved was 50°C.
- Compression Ratio - it was found that a large number of whole seeds were present in the extrudate when using the 1:1 and 2:1 compression ratio screws, therefore it was decided to use 3:1, 4:1 and 5:1 compression ratio screws for the set of experiments.
- Die Size - the throughput of the extruder was inconsistent and prone to blocking at die sizes below 3 mm. An increase in machine throughput was observed with an increase in die size.

5.5.2 Ram press

A ram press was designed and manufactured to enable a standard oil extractability test to be carried out on each of the extruded samples obtained from the experiment.

5.5.2.1 Press design criteria

The press was an important tool in the research in identifying the performance of a large number of preparation treatments, hence it was important to design a press that would provide a rapid and efficient standardised pressing process. The following operational criteria for the press were identified.

- Be relatively quick and easy to operate to ensure the process is practical for the large number of treatments to be assessed.

- Have a high pressing efficiency to ensure that it is possible to be able to differentiate between the performance of the preparation treatments. If the pressing process is not of a high enough efficiency there would be a risk that the residual oil remaining in the press cake would be a factor of the press limitations rather than the preparation treatment.
- Be repeatable to ensure that the process is consistent throughout the experiment set.

5.5.2.2 Press Design

A press meeting the operational criteria was designed and manufactured. The assembly drawing of the press can be seen in Figure 5.2.

The barrel assembly is attached to the base of the press with 2 bolts. This enables the barrel and base to be easily separated for the removal of press cake from the barrel after pressing and cleaning between samples.

The press design provides efficient oil drainage of barrel. Oil is drained through the press cage at the base of the barrel and through a 0.5 mm gap between the barrel and piston. A terylene fabric oil filter is inserted between the cage and barrel to prevent press material being forced through the 1 mm gap of the press cage. The top of the piston is indented to retain the oil that is expelled from the press chamber between the piston and barrel, this prevents oil from re-entering the pressed sample when the pressure on the press cake is released following the press.

The barrel is heated during the press cycle by a 450 watt electric band heater. The temperature of the barrel is monitored and controlled using a CAL 9900 autotune PID temperature controller with a two wire PT100 resistance thermometer. The heater and controller enable an accurate and consistent temperature throughout the press material during the pressing operation. The press barrel is insulated with fibreglass pipe insulation to stabilise the barrel temperature and reduce the cooling rate of the barrel between samples. Accurate control of the barrel temperature is essential to ensure that the press process is consistent throughout the experiment set.

Force is applied to the press piston by means of an Avery press. The force being exerted to the piston is accurately measured and controlled which, as with the temperature control, is essential to ensure consistency and repeatability between press samples throughout the experiment set.

A picture of the ram press on the Avery press bed showing the insulated barrel and the CAL 9900 autotune PID temperature controller is shown in Figure 5.3.

5.5.2.3 Press Operation

A number of pilot trials were completed at a range of operating variables prior to the main set of experimentation to enable the satisfactory development of the standardised pressing process. The major findings from the pilot trials are highlighted below.

- Temperature - at ambient temperature a high press load is required before any oil is expelled from the extrudate. Heating the extrudate lowers the viscosity of the oil and enhances the performance of the press resulting in a greater percentage of oil being expelled from the press material. However, at temperatures in excess of 70°C the press material becomes soft and is forced through the gap between the side of the piston and barrel.

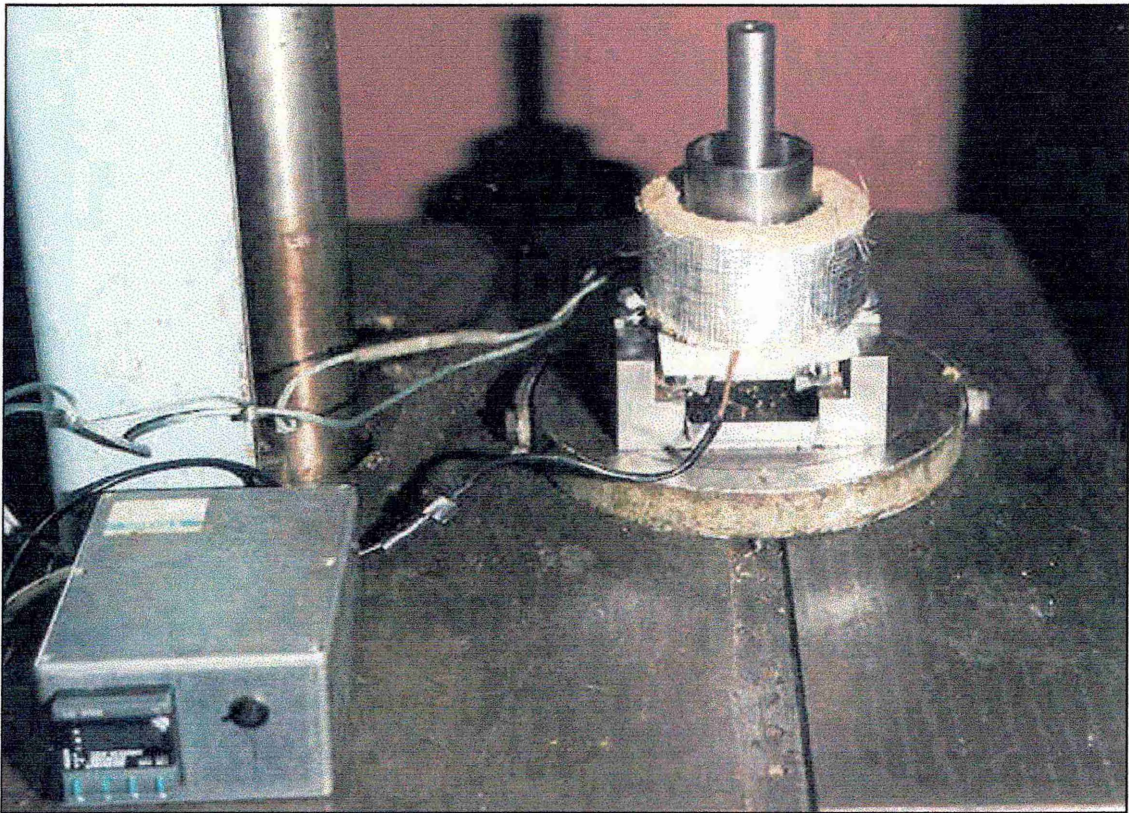


Figure 5.3 *Ram press on the Avery press bed showing the insulated barrel and temperature controller used in the laboratory scale extrusion experiments*

- Press Load - a greater percentage of oil is expelled from the press material as the loading on the press is increased. However, at loads in excess of 60 kN, equivalent to 21 MPa internal press pressure, and at a temperatures of 70°C and above, press material is forced through the gap between the side of the piston and barrel.
- Pressing Time - it was observed during the pilot trials that the majority of the oil was expressed from the press material during approximately the first 3 minutes of pressing.

- Extrusion / Press Interval - the effect that the time interval, between extrusion and pressing, has on the press performance is an important factor to realise when designing the experimental procedure. A trial was carried out pressing extrudate, stored in sealed containers in an oven at 70°C, at time intervals 0.5 hr, 1 hr, 2.5 hr and 3 hr from the time of extrusion. The results from experiment, seen in Appendix C, show that there is no significant difference in press efficiency due to the time interval between extrusion and pressing within a range of 0.5 and 3 hours.

The standardised pressing process conditions, derived from the pilot trials, for use in the experiment set are detailed below.

Pressure	21 MPa (equivalent to 60 kN. force on Avery press)
Holding time	5 minutes
Weight of sample	50g
Temperature of sample	70°C

Extrudate is sealed in a labelled container immediately following extrusion and held in an oven at 70 °C for a period of up to 3 hours prior to pressing.

5.5.3 Power measurement

Accurate measurement of the power requirement for the extruder at the different extrusion variables is measured and recorded using the following equipment.

Current is measured using an ISO.TECH ICA31 AC current transducer. The transducer is connected to a Kiethley 177 DVM (digital volt meter) to convert AC to DC. The transducer has been calibrated against the DVM for increased accuracy and is shown in Figure 5.4.

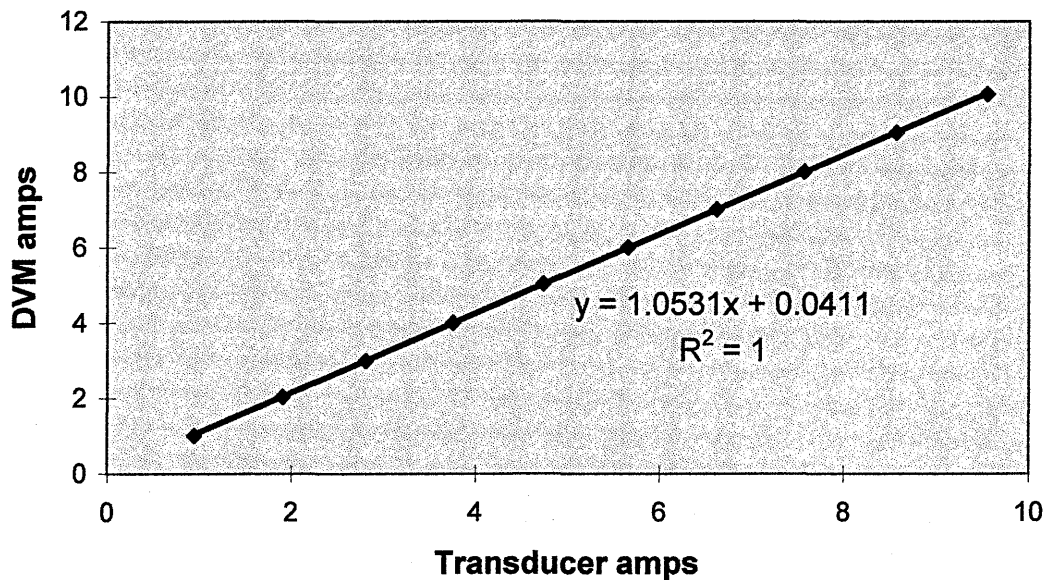


Figure 5.4 Current transducer calibration graph showing correction factor to be applied to the current measurement.

Voltage is measured directly by a second Kiethley 177 DVM.

The two DVM's were connected to a Delta T data logger which logs the amps and voltage at 5 second intervals throughout each extrusion run. Data is then downloaded into microsoft excel where the correction factors for the current transducer and extruder motor power factor, shown in Figure 5.5, can be applied.

A typical graphical representation of the data collected by the data logger during an extrusion run can be seen in Figure 5.6. The peaks on the graph clearly show when the heaters cut in increasing the energy demand of the extruder.

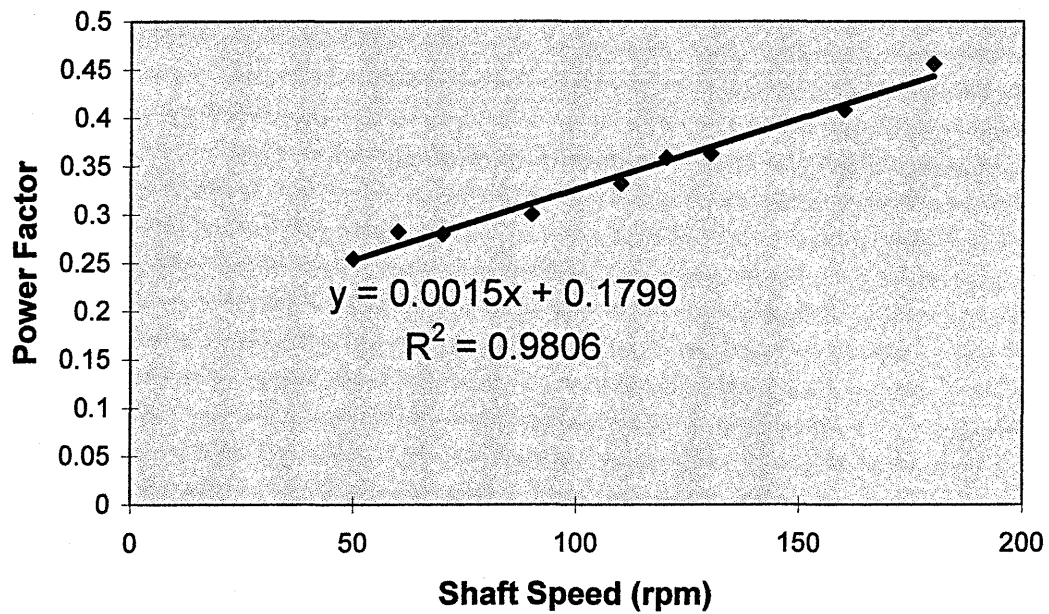


Figure 5.5 Extruder motor power factor calibration graph at varying shaft speeds

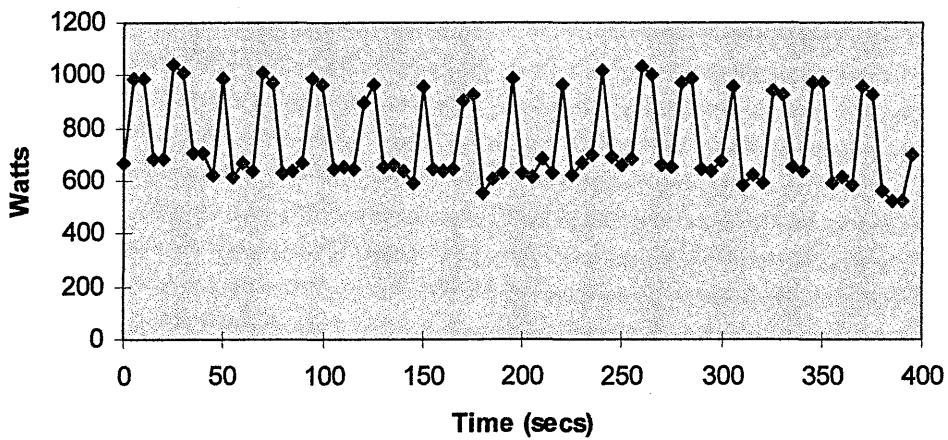


Figure 5.6 An example of a graph showing the power requirement of the extruder measured at 5 second intervals used to calculate the power requirement of the extruder

5.6 Laboratory experiment 1. The effect rapeseed moisture content has on the preparation efficiency of the extruder.

The moisture content experiment was carried out to assess the effect that the moisture content of the rapeseed has on the efficiency of extrusion as a preparation treatment prior to pressing.

It was decided that seven samples of rapeseed with moisture contents ranging from 10% db. (dry base) to as low as could be achieved within a sensible time span would be used for the experiment.

5.6.1 Moisture Conditioning

The moisture content of the rapeseed in store was 7.7% db.

Five 1 Kg samples of rapeseed were conditioned in a thin layer drier for varying lengths of time to produce a range of moisture contents. The temperature of the drier was set at 40°C so as not to cook the seed and subsequently effect the seed structure.

One 1 Kg sample was wetted in sealed containers for approximately 60 hours to produce a sample with a moisture content of approximately 10%. The containers were regularly mixed to ensure homogeneous wetting.

Following the moisture conditioning of the rapeseed samples, the moisture contents of each sample were analysed as detailed in Chapter 4. The actual moisture contents of the seven samples used for the experiment are listed in Table 5.1

5.6.2 Experiment Variables

The standardised set of extruder operating variables chosen for the experiment are detailed in Table 5.1

Table 5.1 *Process variables for laboratory experiment 1. The effect of moisture content on extrusion*

Rapeseed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rev/min)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
10.1	70	90	5	4:1	
7.7					
6.1					
4.5					
4.1					
2.8					
2.5					
7	1	1	1	1	7

The order of turn in which the rapeseed samples were extruded was randomised prior to the experiment.

5.6.3 Results

The % oil in cake (OIC) was measured after both extrusion and pressing processes.

Figure 5.7 clearly shows the effect the moisture content (% MC) of the rape seed has on the process efficiency.

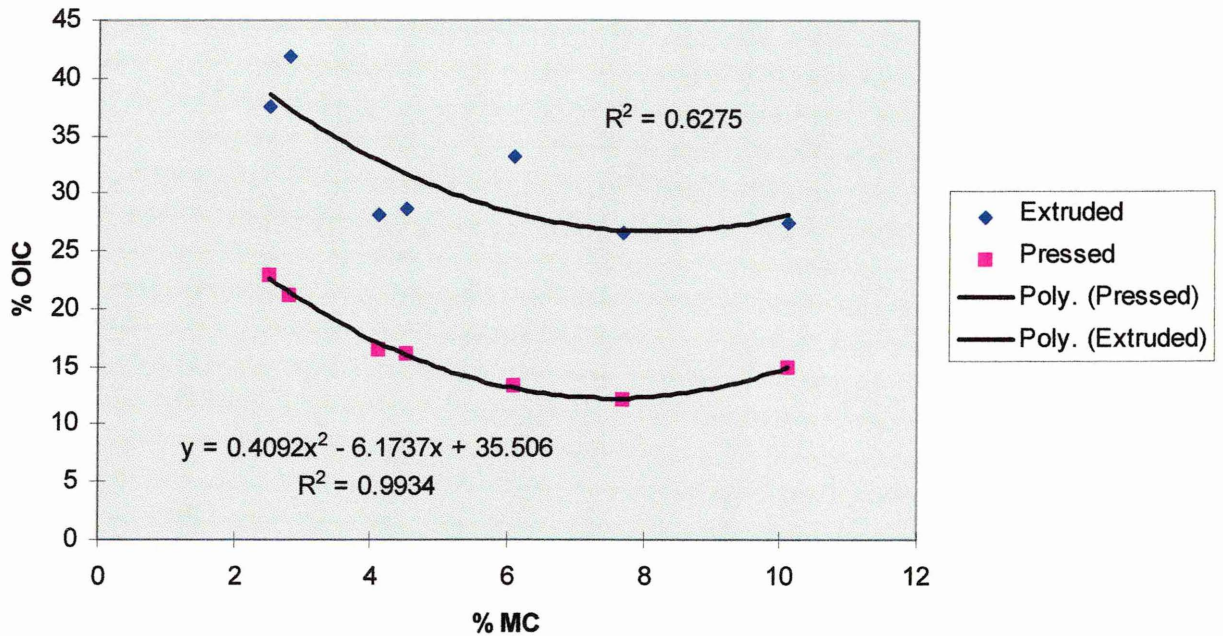


Figure 5.7 *Effect of moisture content on extruder performance before and after pressing*

A strong relationship between the moisture content of the extruded rapeseed and the efficiency of preparation, represented by the % residual oil in the press cake, is evident from the R^2 value of 0.9934 shown in Figure 5.7.

The lowest % OIC following the pressing stage was achieved at 7.7% MC db. At this MC the process efficiency reached 71.4%. The process efficiency became progressively less as the moisture content was reduced. At 2.5% MC the process efficiency was as low as 46.0%. The process efficiency also reduced at MC greater than 7.7% with a process efficiency of 65.2% at 10.1% MC. The table of results for experiment 1 can be seen in Appendix D.

The theoretical optimum moisture content is calculated by differentiating the polynomial curve (pressed) equation shown in Figure 5.7 where:-

$$y = 0.4092x^2 - 6.1737x + 35.506$$

$$\frac{dy}{dx} = 0.8184x - 6.1737$$

$$\text{let } \frac{dy}{dx} = 0$$

$$x = \frac{6.1737}{0.8184} = 7.54\%$$

The theoretical optimum moisture content of rape seed for maximum preparation efficiency is 7.54%

5.7 Laboratory experiment 2. Effect of extrusion temperature on the microstructure of extruded rapeseed.

The experiment was carried out to assess the effect extrusion temperature, above those temperatures traditionally used in the preparation of rapeseed, has on the microstructure of the seed. Light microscopy was used to determine the effect on the seed microstructure. An analysis of the % residual oil left in the extruded rapeseed was also carried out to discover if an increased disruption of the seed microstructure resulted in a greater volume of oil released from the seed matrix during the extrusion process.

5.7.1 Experiment variables

The standardised set of extruder operating variables and rapeseed moisture content chosen for the experiment are detailed in Table 5.2

Table 5.2 *Process variables for laboratory experiment 2. The effect of extrusion temperature on the microstructure of extruded rapeseed*

Rape seed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rpm)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
7	115 135 155 175	100	7	4:1	
1	4	1	1	1	4

5.7.2 Results

The microstructure of the processed rapeseed, including the oil cells, are clearly visible with light microscopy. The effect that the extrusion temperature has on the microstructure of the rapeseed during the extrusion process can be seen in Figure 5.8.



*Plate I Rapeseed extruded
at 115 °C*



*Plate II Rapeseed extruded at
135 °C*



*Plate III Rapeseed extruded
at 155 °C*



*Plate IV Rapeseed extruded at
175 °C*

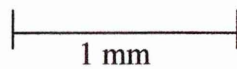


Figure 5.8 *Microstructures of extruded rapeseed at a range of processing temperatures*

An interesting observation from the microscopy is that it would appear from these sections that greater destruction of the seed structure has taken place at lower temperatures. At 115°C fewer oil cells are visible and larger areas of 'mashed' cells, indicated by deep red areas as indicated by the letter A, Plate I, are more evident than at higher temperatures. Larger areas of whole cells, as indicated by the letter B, Plate IV, are apparent as the extruded temperature increases.

The observations from the microscopy are supported by oil content analysis of the extruded samples. It can be seen in Figure 5.9 that of the four samples examined, the greatest amount of oil was released from the seed matrix at extrusion temperature 115°C, the same temperature at which the greatest seed structure destruction was observed. The results table for the experiment can be seen in Appendix E.

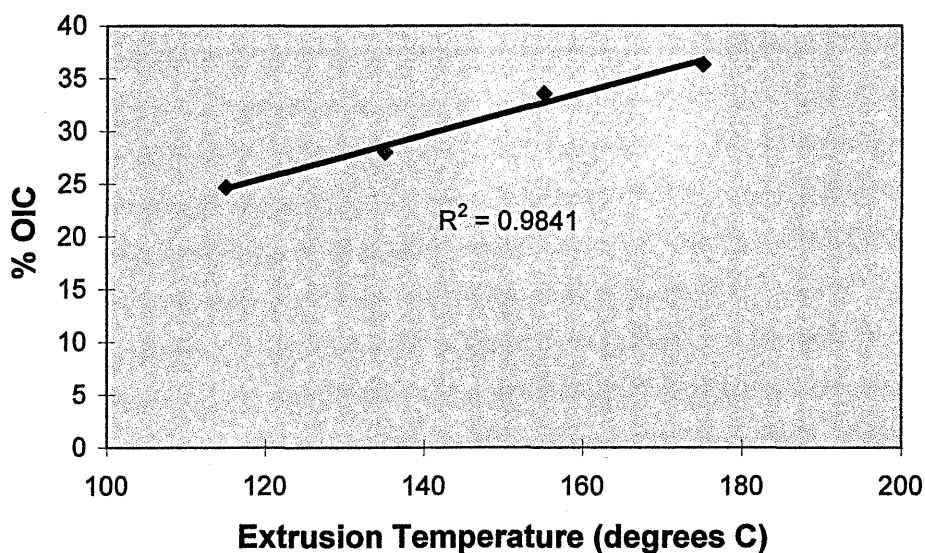


Figure 5.9 *The effect extrusion temperature has on % residual oil in the extruded rapeseed*

A further, and again interesting, observation gained from this experiment is the R^2 value of 0.9841 shown in Figure 5.9. This indicates that, at the temperature range examined, the % OIC after extrusion is directly related to the extrusion temperature. However, at this stage of experimentation the actual relationship between extrusion temperature and the release of oil during extrusion is not conclusive. A greater range of extrusion temperatures needs to be examined before a definite relationship can be realised.

5.8 Laboratory experiment 3. The effect extrusion operating variables have on the efficiency of the process as a preparation treatment

Experiment 3 is the largest of the laboratory scale experiments completed for the research. The experiment examines 108 extrusion process condition combinations and is designed to assess the effects that the individual extrusion operating variables have on the preparation efficiency. The experiment will also reveal any interactions between individual operating conditions that effect the preparation process.

Due to the large number of process conditions being examined, with each individual operating variable being applied at least 27 times during the process condition combinations, statistically it was not considered necessary to repeat each of the 108 extrusion process condition combinations during the experimentation.

5.8.1 Experiment variables

The extruder operating variables and rapeseed moisture content chosen for the experiment are detailed in Table 5.3

Table 5.3 *Process variables for laboratory experiment 3. The effect extrusion operating variables have on the efficiency of the process as a preparation treatment*

Rapeseed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rpm)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
7	80	90	5	3:1	
	100	120	6	4:1	
	120	150	7	5:1	
	140				
1	4	3	3	3	108

5.8.2 Analysis of results

A statistical analysis of the experiment data was carried out to assess the effect that the individual process variables and any interrelation between these variables have on the oil extraction efficiency of the process together with the effects on the power requirements and the throughput of the extruder. The residual analysis showed no regular pattern and did have a normal distribution.

An examination of the seed microstructure and a milling defect analysis were carried out on a sample of the 108 extrusion process condition combinations assessed.

5.8.2.1 Residual oil analysis

A full set of results and the statistical analysis for the residual oil analysis is shown in Appendix F. The major points of interest from the results are detailed in the following section.

The F probabilities of the analysis of variance for the effects of extrusion process variables on the residual oil content of pressed extrudate is shown in table 5.4.

Table 5.4 *F probabilities of the analysis of variance for the effects of extrusion process variables on the residual oil content.*

Source of variation	F pr.
Barrel temperature (temp)	< 0.001*
Screw speed (speed)	< 0.001*
Die size (die)	0.023 *
Compression ratio (CR)	<0.001*
temp. speed	0.213
temp. die	0.955
speed. die	0.411
temp. CR	0.011*
speed. CR	0.722
die. CR	0.084
temp. speed. die	0.099
temp. speed. CR	0.833
temp. die .CR	0.601
speed. die. CR	0.629

*Significant

The analysis of variance shows that all four process variables used in the trial are independently significant and that there is also significant interaction between the barrel temperature and screw compression ratio. There is no other significant relationship between the process variables.

The tables of means for each of the individual process variables show the effect that the variables have on the oil extraction process. The least significant differences of the means (l.s.d.) for each significant process variable and variable interaction has been calculated and discussed.

Barrel temperature

Table 5.5 *Barrel temperature table of means and l.s.d.*

Barrel temperature (°C)	80	100	120	140
Mean % OIC after press	11.4	12.4	14.5	17.6
l.s.d	0.5552			

Table 5.5 and the accompanying graph, shown in Figure 5.10, show that the efficiency of the rapeseed preparation, indicated by the mean % OIC after pressing, is enhanced at lower extrusion temperatures. The l.s.d. for the barrel temperatures show that for each incremental reduction in temperature of 20°C the preparation efficiency significantly improves.

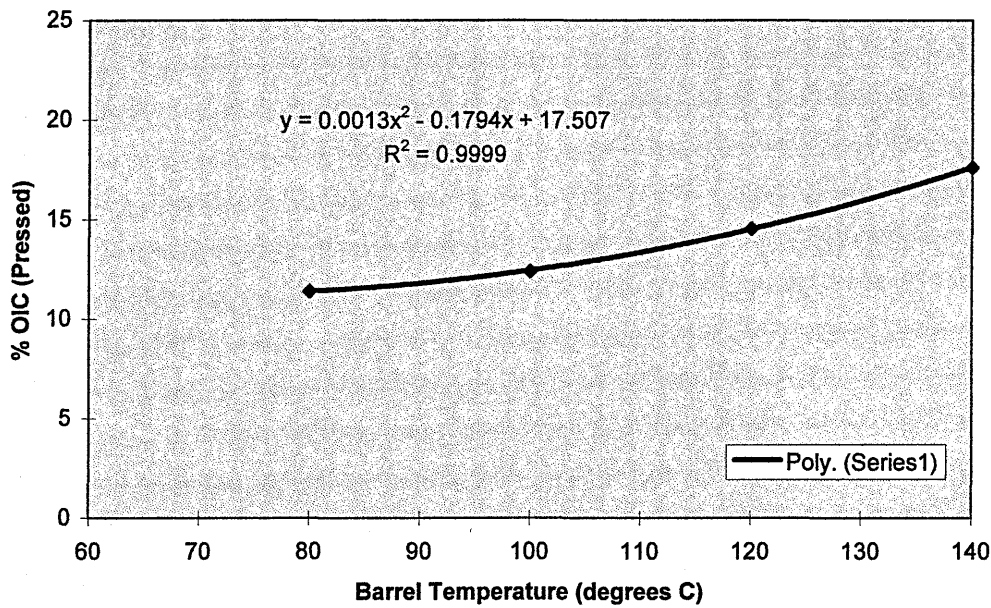


Figure 5.10 *Effect extruder barrel temperature has on the mean % OIC after pressing*

The results from this trial backs up previous microscopy work which indicated that greater cell damage occurs during the extrusion process at lower temperatures. It was considered that further trials at lower temperatures should be carried out to see if the trend seen in Figure 5.10 continues. It should be noted that the % OIC means, and the significance between extrusion temperatures, treated the effect of temperature as an independent variable and did not account for the interaction between extrusion temperatures and screw compression ratios.

Screw Speed

Table 5.6 and the accompanying graph, shown in Figure 5.11, show that the lowest mean % OIC after pressing occurs at the lowest screw speeds. The l.s.d. for the screw speeds demonstrates that at a screw speed of 90 rev/min, the effectiveness of preparation significantly surpasses that at 120 and 150 rev/min. There is no significant difference in the preparation effectiveness at screw speeds of 120 and 150 rev/min.

Table 5.6 *Screw speed table of means and l.s.d.*

Screw speed. (rev/min)	90	120	150
Mean % OIC after press	13.2	14.2	14.6
l.s.d	0.4809		

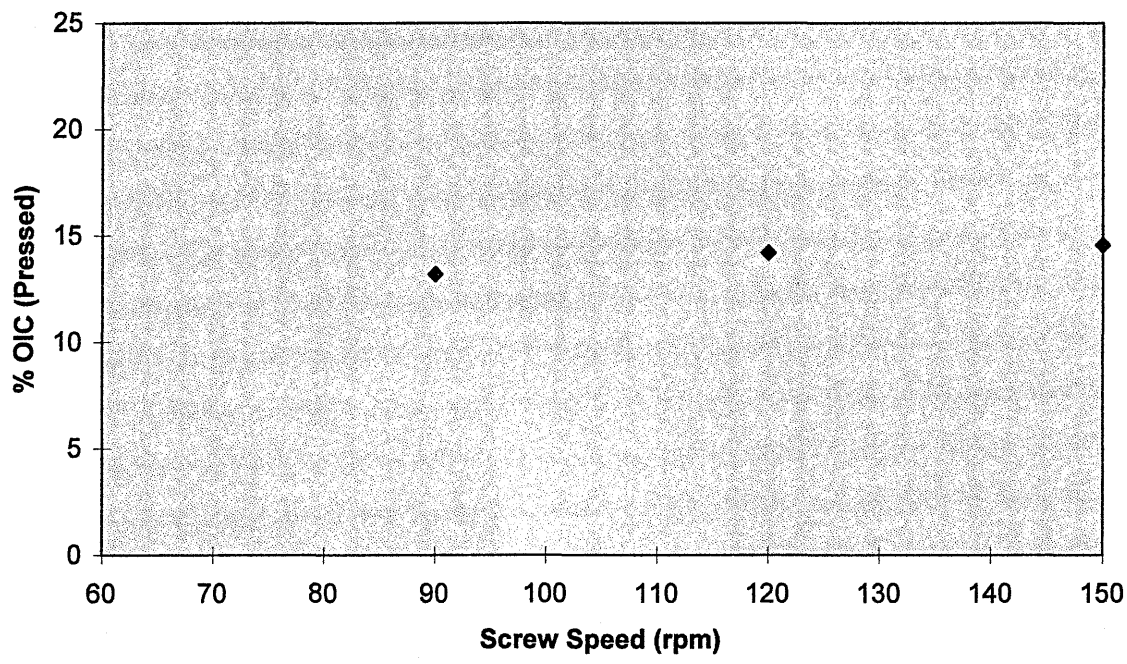


Figure 5.11 *Effect extruder screw speed has on the mean % OIC after pressing*

Die Size

Table 4.7 and the accompanying graph, shown in Figure 5.12, show that the lowest mean % OIC after pressing occurs at the lowest die size. The l.s.d. for the die sizes demonstrates that with a 5 mm diameter die the effectiveness of preparation is significantly better than with a 7 mm diameter die. The l.s.d also reveals that there is no significant difference in the effectiveness of preparation between using a 5 mm or 6 mm diameter die or between using a 6 mm or 7 mm diameter die. A difference in die diameter of 1 mm does not effect the preparation effectiveness.

Table 5.7 *Die size table of means and l.s.d.*

Die size. (mm)	5	6	7
Mean % OIC after press	13.6	14.0	14.3
l.s.d.	0.4809		

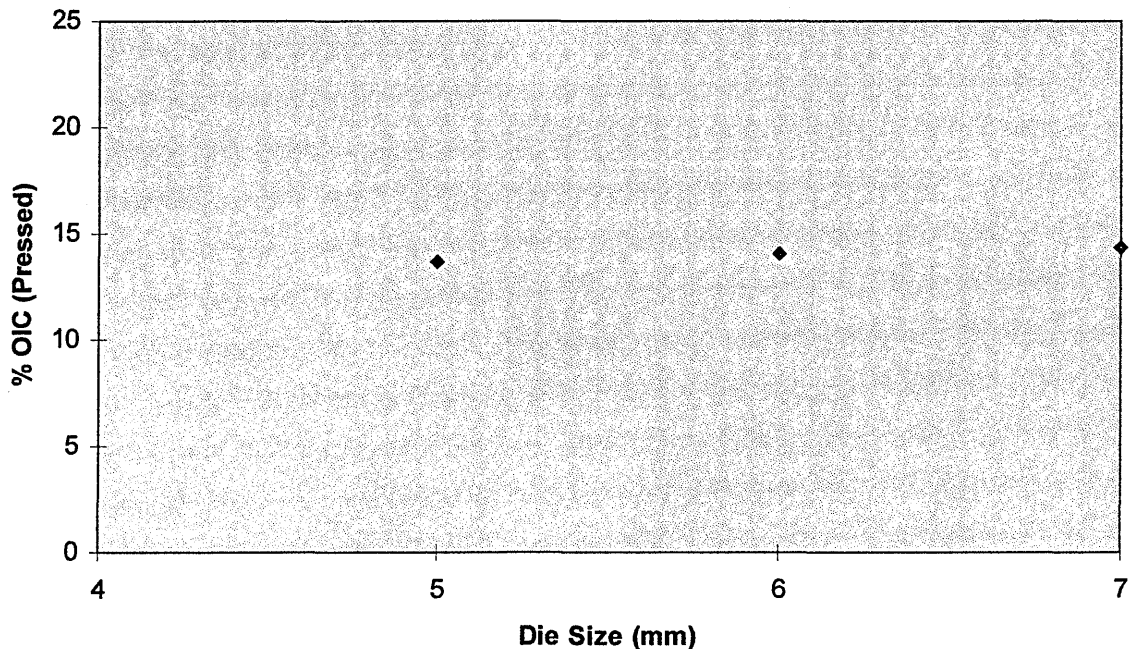


Figure 5.12 *Effect extruder die size has on the mean % OIC after pressing*

Compression Ratio

Table 5.8 and the accompanying graph, shown in Figure 5.13, show that the lowest mean % OIC after pressing occurs at the highest compression ratio examined. The l.s.d. for the compression ratios demonstrate that with a 5:1 screw compression ratio the effectiveness of preparation is significantly better than with a 4:1 or 3:1 screw compression ratio. The l.s.d. also reveals that there is no significant difference in the effectiveness of preparation between using a 4:1 or 3:1 screw compression.

It should be noted that the % OIC means, and the significance between screw compression ratios, treated the effect of screw compression ratio as an independent variable and did not account for the interaction between compression ratios and extrusion temperatures.

Table 5.8 *Compression ratio table of means and l.s.d.*

Compression ratio	3:1	4:1	5:1
Mean % OIC after press	14.5	14.5	13.0
l.s.d.	0.4809		

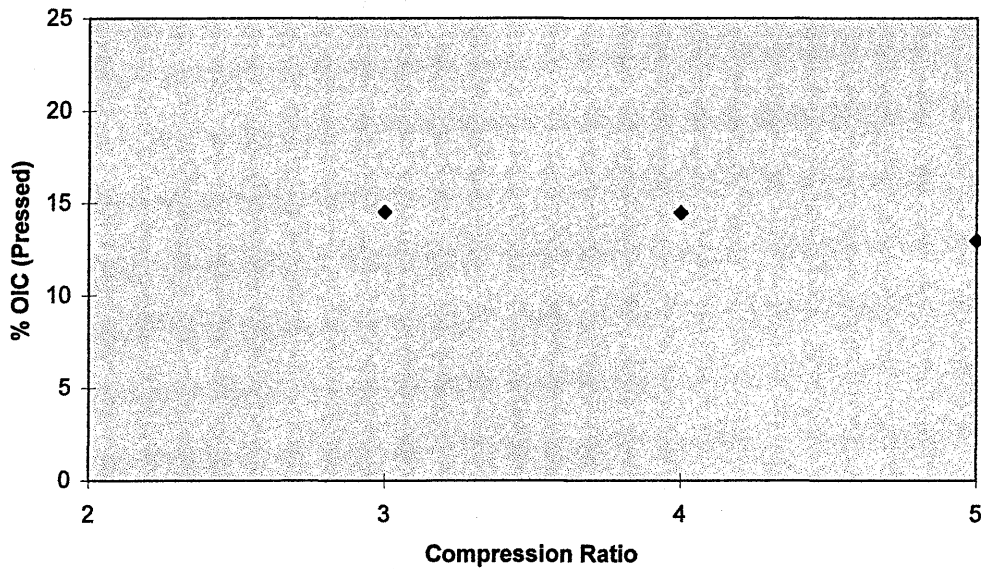


Figure 5.13 *Effect extruder screw compression ratio has on the mean % OIC after pressing*

Temperature / Compression ratio

Table 5.9 and the accompanying graph, shown in Figure 5.14, show that at an extruder barrel temperature of 80°C, the different compression ratios examined in the experiment have no significant effect on the effectiveness of the preparation of rapeseed for oil extraction with a press. At barrel temperatures in excess of 80°C a 5:1 screw compression ratio performed significantly better than compression ratios 3:1 and 4:1. At these elevated temperatures there was no significant difference in preparation performances between compression ratios 3:1 and 4:1.

At compression ratios 3:1 and 4:1 the preparation was significantly enhanced with every incremental drop in the barrel temperature. However, at 5:1 there was no significant difference in preparation performance between the two barrel temperatures of 80°C and 100°C.

Table 5.9 *Extruder barrel temperature / screw compression ratio table of means and l.s.d.*

	Compression Ratio		
Temperature (°C)	3:1	4:1	5:1
80	11.4	11.6	11.3
100	13.2	12.6	11.5
120	15.4	15.2	13.0
140	18.2	18.6	16.1
l.s.d.	0.9617		

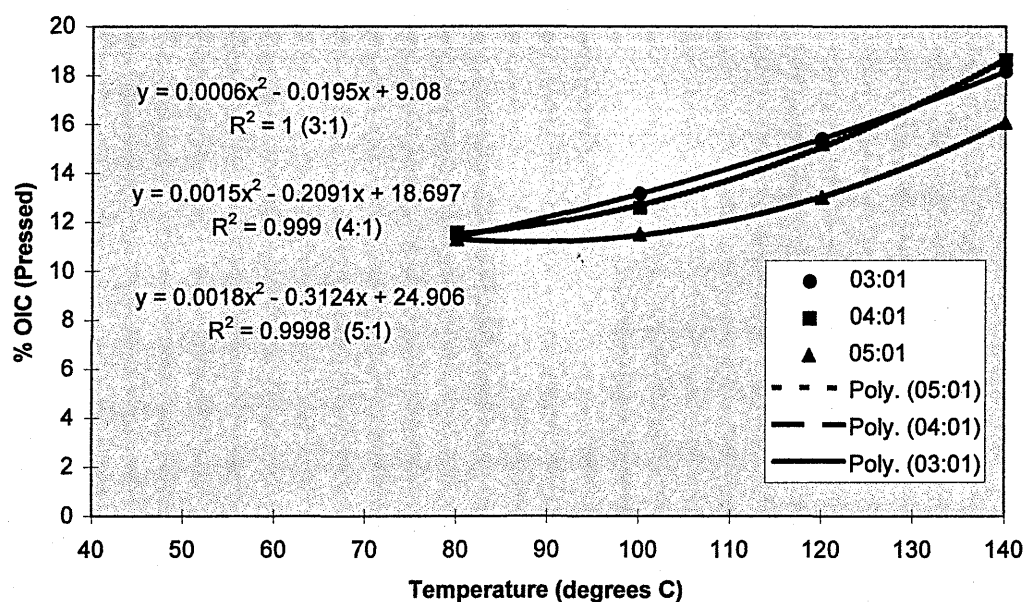


Figure 5.14 *Effect the interaction between extruder barrel temperature and screw compression ratio has on the % OIC after pressing*

The results suggest that no advantage is gained in effectiveness of the preparation of rapeseed by extruding with screw compression ratios above 3:1 as long as the extruder barrel temperature is not in excess of 80 °C.

There was however still a question whether the effectiveness of preparation could yet still be enhanced with a further reduction in process temperature. The graph in Figure 5.14 shows the barrel temperature / % OIC (pressed) curve for each of the screw compression ratios examined as having a strong polynomial relationship with an R^2 figure very close to 1. It is therefore possible to identify the theoretical optimum extrusion barrel processing temperature for each of the compression ratios examined by differentiating each of the curve equations to find the temperature when the gradient of the curve is equal to zero. The calculated theoretical optimum extruder processing temperatures for screw compression ratios 3:1, 4:1 and 5:1 are shown in Table 5.10.

Table 5.10 *Theoretical optimum extruder operating temperatures for screw compression ratios 3:1, 4:1 and 5:1.*

Compression ratio	Optimum operating temperature
3:1	16 °C
4:1	70°C
5:1	87°C

The table shows that the optimum temperature for a 3:1 compression ratio is 16°C. To operate an extruder at this low a temperature would require substantial cooling due to the heat generated from friction within the extruder barrel. It should be noted that the processing temperatures quoted in Table 5.10 are theoretical and assume that the data points in Figure 5.14 would continue having a strong polynomial relationship over a greater range of processing temperatures than were assessed in the experiment. A greater range of data points would be required before a confident quote of optimum processing temperature / compression ratio combination is made.

5.8.2.2 Power requirement

A full set of results and the statistical analysis for the power requirement analysis is shown in Appendix G. The major points of interest from the results are detailed in the following section.

The F probabilities of the analysis of variance for the effects of extrusion process variables on the power requirement of the process is shown in Table 5.11.

Table 5.11 *F probabilities of the analysis of variance for the effects of extrusion process variables on the process power requirement.*

Source of variation	F pr.
Barrel temperature (temp)	0.007*
Screw speed (speed)	0.002*
Die	0.476
Compression ratio (CR)	<0.001*
temp. speed	0.209
temp. die	0.082
speed. die	0.110
temp. CR	0.532
speed. CR	0.170
die. CR	0.216
temp. speed. die	0.026*
temp. speed. CR	0.551
temp. die .CR	0.472
speed. die. CR	0.145

* significant

The analysis of variance shows that the barrel temperature, screw speed and the screw compression ratio are all independently significant variables to the power requirement for the extrusion process. The analysis also suggests a three way significant interaction between the barrel temperature, screw speed and die size. There is no other significant relationship between the process variables.

The tables of means for each of the significant individual process variables show the effect that the variables have on the power requirement for the process. The least significant differences of the means (l.s.d.) for each significant process variable and variable interaction has been calculated and discussed.

Barrel temperature

Table 5.12 and the accompanying graph shown in Figure 5.15, show that the power requirement for the extrusion process in the preparation of the rapeseed, measured in joules per gram of processed seed, is significantly greater at 140°C than at the other lower temperatures examined during the experiment. The statistical analysis also show that there is no significant difference in the power requirement of the extrusion process when extruding at 80, 100 or 120°C.

Table 5.12 *Barrel temperature table of means and l.s.d.*

Barrel Temp. (°C)	80	100	120	140
Mean joules / g	347.99	340.65	346.83	363.73
l.s.d	12.729			

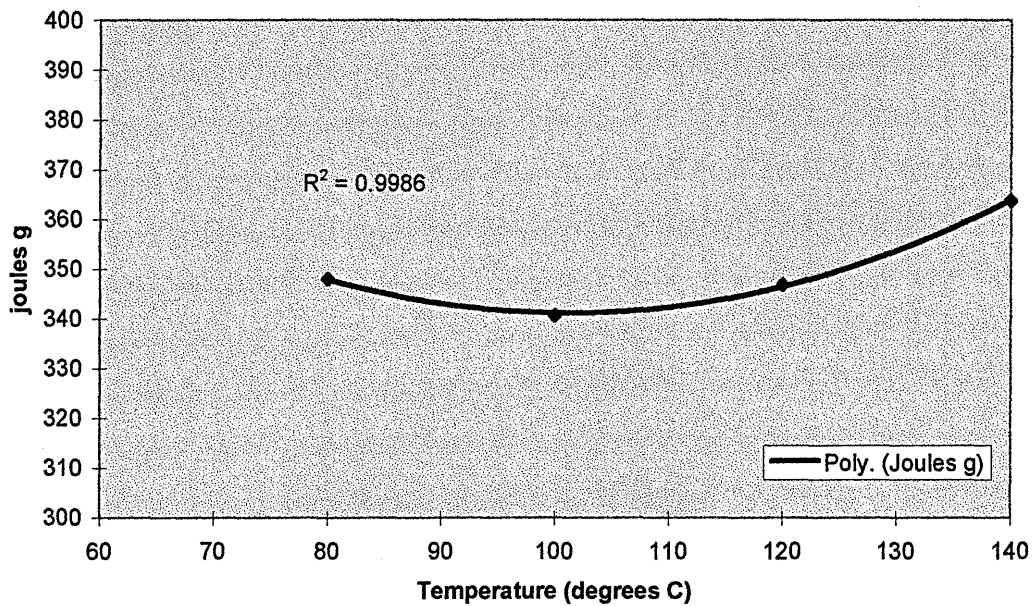


Figure 5.15 Effect extruder barrel temperature has on the mean power requirement for extrusion (J/g)

Screw Speed

Table 5.13 and the accompanying graph, shown in Figure 5.16, show that the power requirement for the extrusion process in the preparation of the rapeseed is significantly greater at a screw speed of 150 rev/min than at screw speeds of 90 and 120 rev/min. The analysis also shows that there is no significant difference in the power requirement of the extrusion process at screw speeds of 90 and 120 rev/min.

Table 5.13 Screw speed table of means and l.s.d.

Screw Speed. (rev/min)	90	120	150
Mean J/g	342.94	343.94	362.51
l.s.d	11.024		

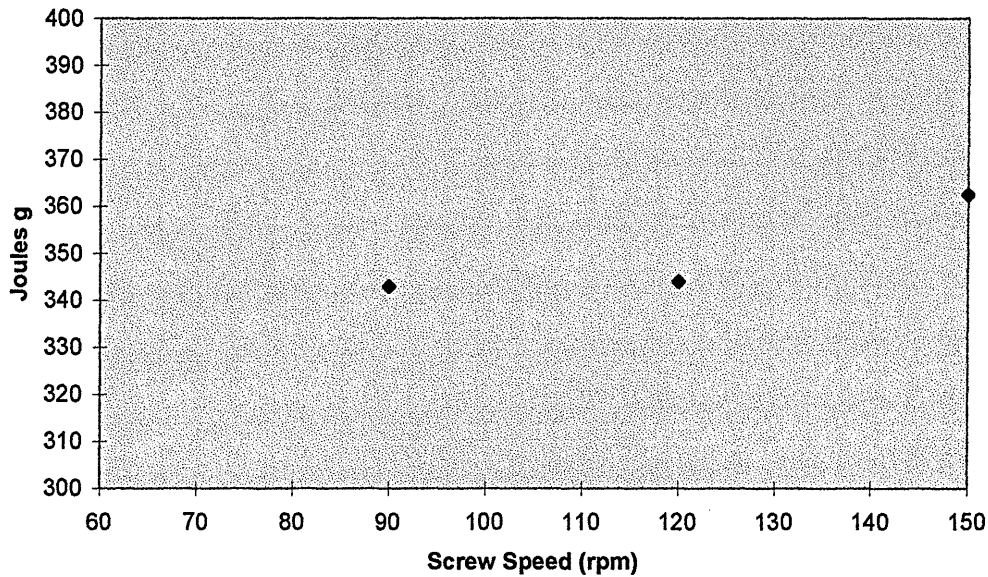


Figure 5.16 Effect extruder screw speed has on the mean power requirement for extrusion (J/g)

Compression Ratio

Table 5.14 and the accompanying graph, shown in Figure 5.17, show that the power requirement for the extrusion process in the preparation of the rapeseed is significantly greater at screw compression ratios 4:1 and 5:1 than at a screw compression ratio of 3:1. The analysis also shows that there is no significant difference in the power requirement of the extrusion process at a screw compression ratios of 4:1 and 5:1.

Table 5.14 Compression ratio table of means and l.s.d.

Compression Ratio	3:1	4:1	5:1
Mean J/g	336.31	360.81	352.27
l.s.d.	11.024		

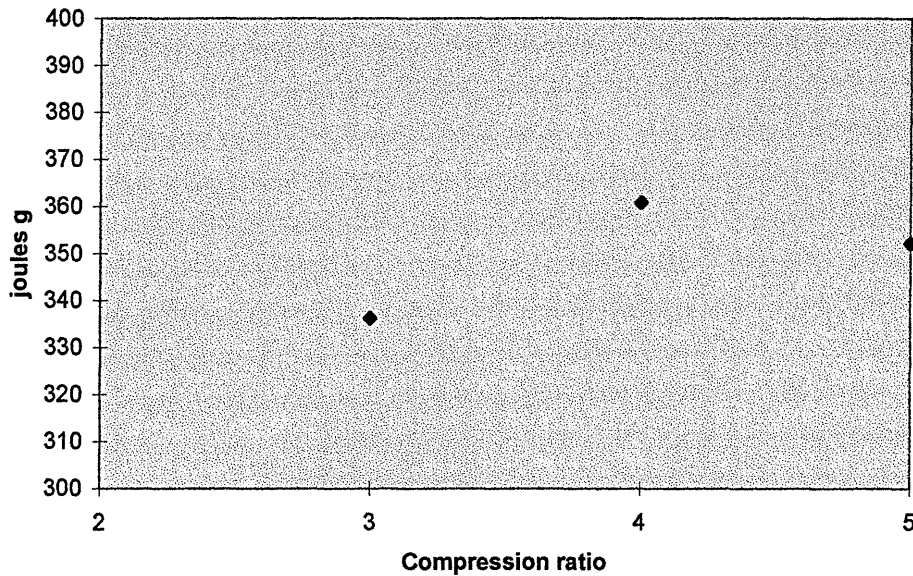


Figure 5.17 *Effect extruder screw compression ratio has on the mean power requirement for extrusion (J/g)*

5.8.2.3 Extruder throughput

A full set of results and the statistical analysis for the extruder throughput analysis is shown in Appendix H. The major points of interest from the results are detailed in the following section.

The F probabilities of the analysis of variance for the effects of extrusion process variables on the extruder throughput is shown in Table 5.15

Table 5.15 *Analysis of variance for the effects of extrusion process variables on the extruder throughput.*

Source of variation	F pr.
Barrel temperature (temp)	0.262
Screw speed (speed)	< 0.001*
Die	0.776
Compression ratio (CR)	0.294
temp. speed	0.589
temp. die	0.025*
speed. die	0.272
temp. CR	0.555
speed. CR	0.287
die. CR	0.012*
temp. speed. die	0.099
temp. speed. CR	0.633
temp. die .CR	0.581
speed. die. CR	0.124

* significant

The analysis of variance shows that the screw speed is the only independently significant variable to the throughput of the extruder. The analysis also suggests there are significant interactions between the barrel temperature and die size and between the die size and screw compression ratio. There are no other significant relationships between the process variables.

The tables of means for the significant individual process variable show the effect that the variables have on the throughput of the extruder. The least significant differences (l.s.d.) of the means for the significant process variable and variable interactions have been calculated and discussed.

Screw Speed

Table 5.16 and the accompanying graph, shown in Figure 5.18, show that the throughput of the extruder increases with screw speed. The l.s.d. for the screw speeds show that for each incremental increase in screw speed of 30 rev/min there is a significant increase in the throughput of the extruder. The increase in extruder throughput is directly related to the extruder screw speed.

Table 5.16 *Screw speed table of means and l.s.d.*

Screw speed. rev/min	90	120	150
Mean joules / g	342.94	343.94	362.51
l.s.d	11.024		

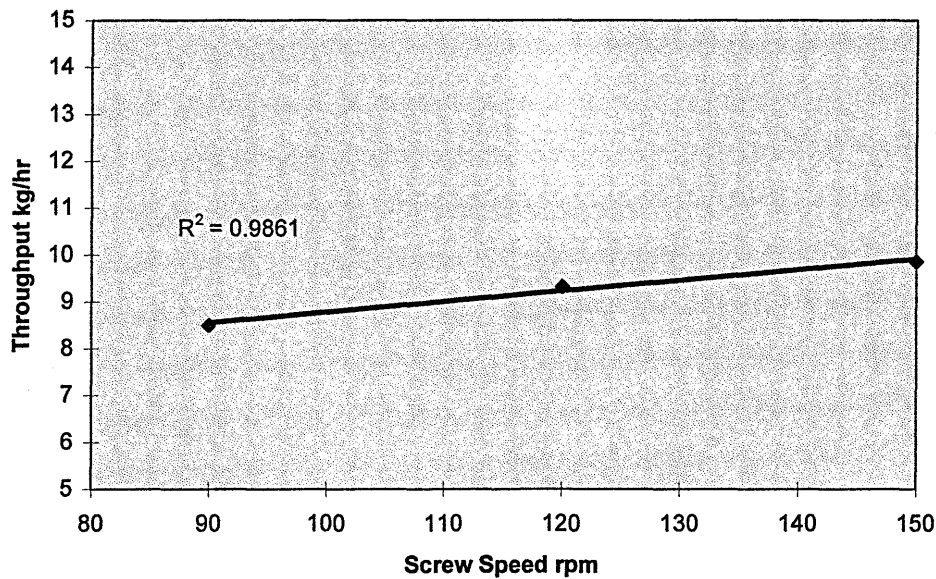


Figure 5.18 *Effect extruder screw speed has on the mean throughput of the extruder (Kg/h)*

5.8.2.4 Microscopy

A selection of extruded samples, from the 108 process condition combinations assessed in the experiment, were selected for an analysis of the seed microstructure with light microscopy. The extruded samples were selected to ensure that the effect that each of the four process variables have on the microstructure of the extruded rapeseed could be individually assessed, and that the selection was unbiased.

Each of the four sample sets were selected to assess the effect of one of the four process variables. The samples within each set were selected so that only one of the four process variables, the variable being assessed, changed and the other three process variables remained constant. By selecting a sample set varying only in one of the process variables, with all the other operating conditions remaining constant, it was ensured that any differences identified in the analysis of the microstructure was exclusively as a result of the effect of the process variable being assessed.

The sample selection process involved one sample being randomly selected from the 108 experiment process conditions for each of the four process variables (extrusion temperature, screw compression ratio, die size and screw speed). The other samples required to complete the set, so that a full range of the process variable being assessed was included, could then be identified and selected.

Temperature

A set of four samples were selected to cover the full range of the extrusion temperatures assessed in the experiment. The constant operating conditions for the sample set were:- screw speed 150 rev/min, die size 7 mm, compression ratio 3:1 and moisture content 7%.

The microstructures of the four samples extruded at 80, 100, 120 and 140°C are shown in Figure 5.19. The microscopy indicates a large difference in the cell structure between Plate I (80°C) and Plate II (140°C). In Plate II large areas of intact seed cell structure are clearly evident. Large unbroken segments of the seed testa encapsulating the seed is also clearly visible in plate II. As the extrusion temperature is decreased the evidence of intact seed cell structure is reduced. In Plate I a large percentage of the cell structure has been damaged with little evidence of the seed structure remaining.

Compression ratio

A set of three samples were selected to cover the full range of the extruder screw compression ratios assessed in the experiment. The constant operating conditions for the sample set were, extrusion temperature 100 °C, screw speed 90 rev/min, die size 7 mm and moisture content 7%.

The microstructures of the three samples extruded at screw compression ratios 3:1, 4:1 and 5:1 are shown in Figure 5.20. The highest percentage of cell damage, of the three microstructures analysed, is apparent in Plate III (compression ratio 5:1). The microstructures in Plate I (compression ratio 3:1) and Plate II (compression ratio 4:1) are very alike revealing similar amounts of damage to the seed cell structure. It can however be said that all three plates do indicate a relatively high percentage of cell structure damage.

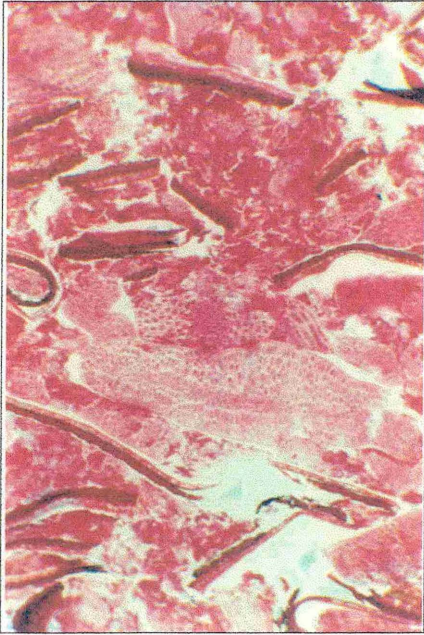


Plate I Temperature 80 °C



Plate II Temperature 100 °C

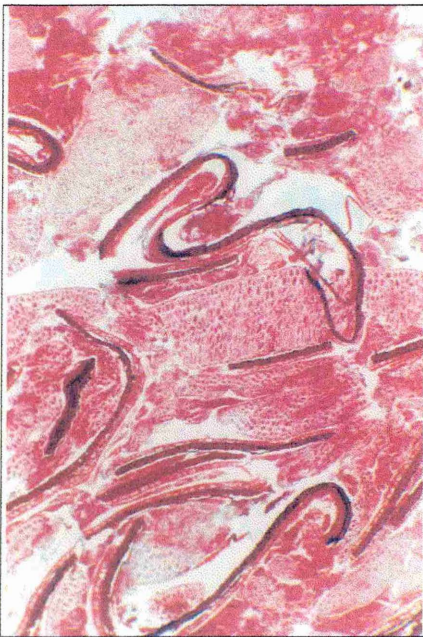


Plate III Temperature 120 °C



Plate IV Temperature 140 °C



1 mm

Figure 5.19 The effect extrusion temperature has on the microstructure of extruded rapeseed. The extruder operating conditions; screw speed 150 rev/min, die size 7 mm and screw compression ratio 3:1 were constant for the four pictured samples.

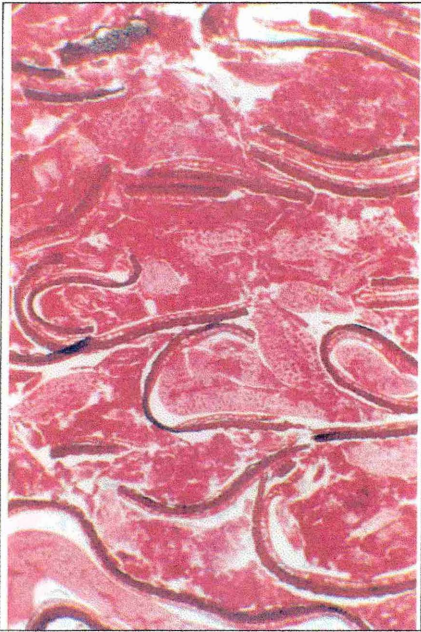


Plate I Compression ratio 3:1

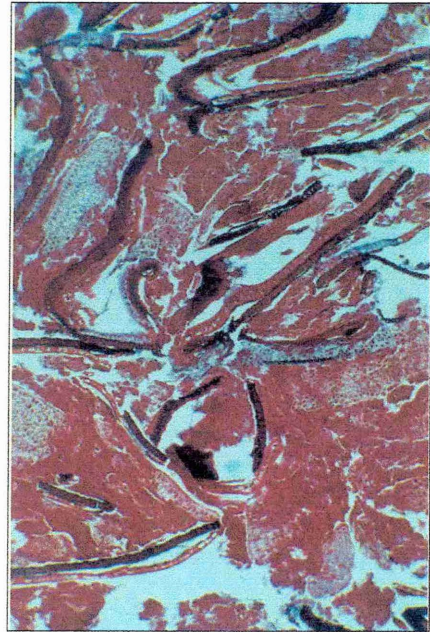


Plate II Compression ratio 4:1



Plate III Compression ratio 5:1

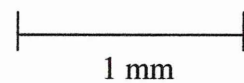


Figure 5.20 The effect extruder screw compression ratio has on the microstructure of extruded rapeseed. The extruder operating conditions; barrel temperature 100 °C, screw speed 90 rev/min and die size 7 mm were constant for the three pictured samples.

Die size

A set of three samples were selected to cover the full range of die sizes assessed in the experiment. The constant operating conditions for the sample set were, extrusion temperature 120°C, screw speed 90 rev/min, screw compression ratio 3:1 and moisture content 7%.

The microstructures of the three samples extruded at die sizes 5, 6 and 7 mm are shown in Figure 5.21. The microscopy reveals that, although there is some difference in the percentage cell damage between the three samples, the difference is not that great. Of the three microstructures analysed, the greatest percentage of cell damage is apparent in Plate I (die size 5 mm). The percentage cell damage appears to become progressively less as the die size is increased with the least cell damage evident in Plate III (die size 7 mm).

Screw speed

A set of three samples were selected to cover the full range of screw speeds assessed in the experiment. The constant operating conditions for the sample set were, extrusion temperature 80°C, screw compression ratio 4:1, die size 6 mm and moisture content 7%.

The microstructures of the three samples extruded at screw speeds are shown in Figure 5.22. All three of the microstructures analysed do indicate a high percentage of cell damage, however, the greatest amount of cell damage, with little evidence of undamaged cells remaining is identified in Plate I (screw speed 90 rev/min). The microstructures in Plate II (screw speed 120 rev/min) and Plate III (screw speed 150 rev/min) are very similar, both of which revealing small clusters of undamaged cells.

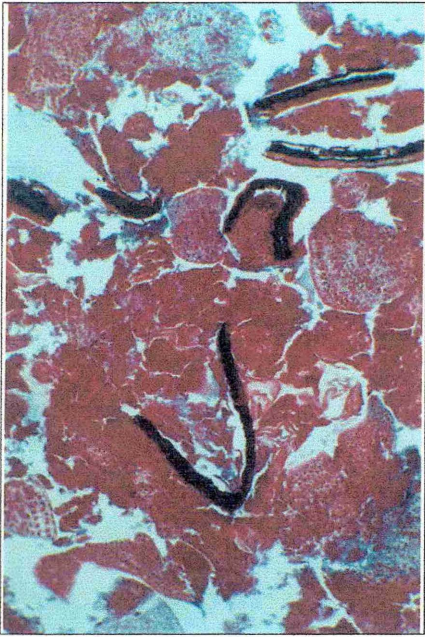


Plate I Die size 5 mm

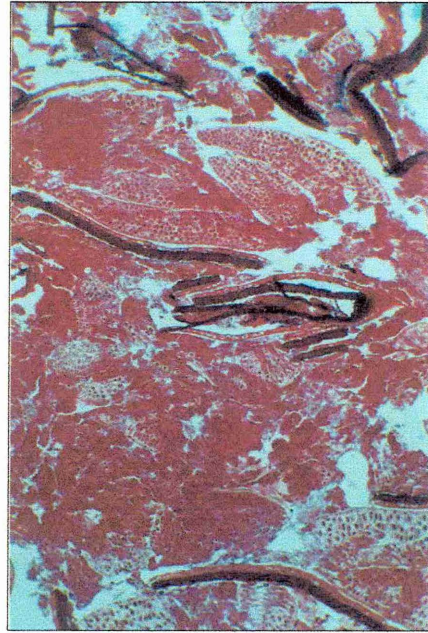


Plate II Die size 6 mm

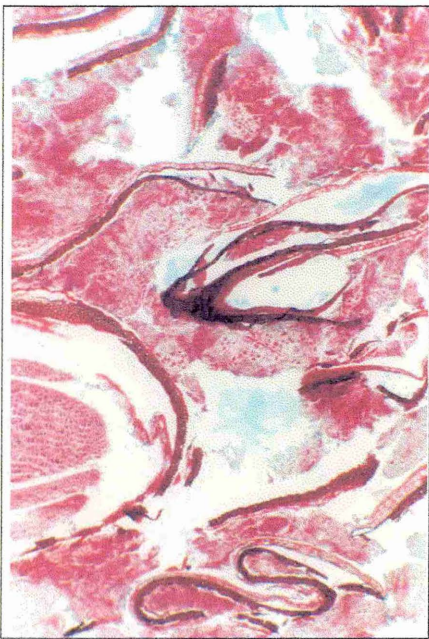


Plate III Die size 7 mm

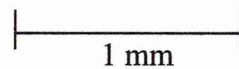


Figure 5.21 The effect extruder die size has on the microstructure of extruded rape seed. The extruder operating conditions; barrel temperature 120 °C, screw speed 90 rev/min and screw compression ratio 3:1 were constant for the three pictured samples.



Plate I Screw speed 90 rev/min

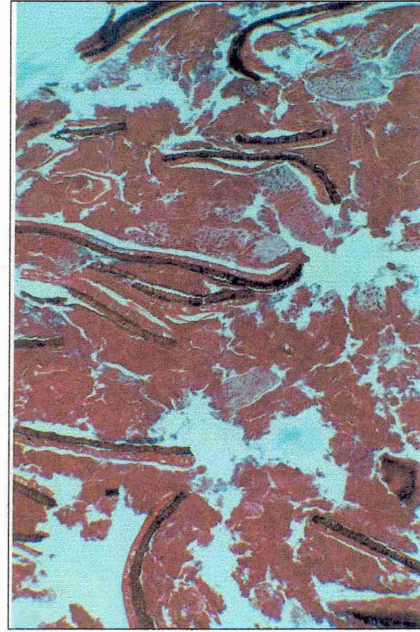


Plate II Screw speed 120 rev/min

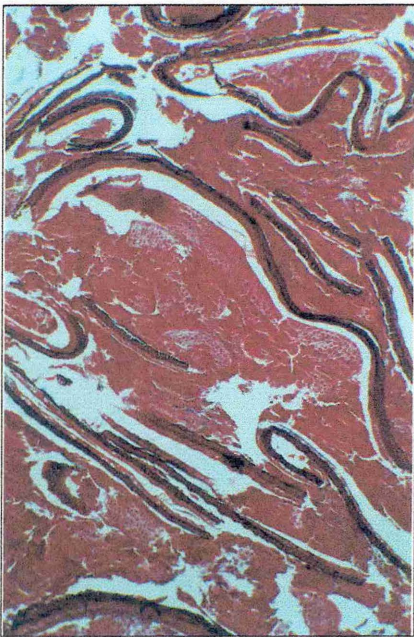


Plate III Screw speed 150 rev/min

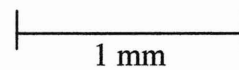


Figure 5.22 The effect extruder screw speed has on the microstructure of extruded rapeseed. The extruder operating conditions; barrel temperature 80 °C, die size 6 mm and screw compression ratio 4:1 were constant for the three pictured samples

5.9 Extrusion experiment 4. Increased temperature range

Extrusion experiment 4 was carried out to discover the effect that lower barrel temperatures have on the oil seed before and after pressing. It was decided that for this experiment the only variable to be changed was the barrel temperature. The screw speed, die size and screw compression ratio used for this experiment were the variables that gave the lowest mean % OIC after pressing in the preliminary trials i.e. 90 rev/min, 5 mm and 5:1 respectively.

5.9.1 Experiment variables

The extruder operating variables and rapeseed moisture content chosen for the experiment are detailed in Table 5.17

Table 5.17 *Process variables for laboratory experiment 4. The effect of temperature on extrusion.*

Rapeseed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rev/min)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
7	50	90	5	5:1	
	60				
	70				
	80				
	100				
	120				
	140				
1	7	1	1	1	7

Number of replications = 2

Total Number of tests = 14

Note: 50°C was the lowest possible operating temperature that could be achieved with the Brabender air cooling system.

5.9.2 Analysis of Results

The full results table for extrusion experiment 4 is shown in Appendix I. The analysis of the results of the experiment are presented below

5.9.2.1 Oil Analysis

A graph showing the results of the residual oil following extrusion prior to pressing is shown in Figure 5.23. The data points in Figure 5.23 between 140°C and 70°C are very much as expected. As with the previous experiment, as the temperature is reduced the % OIC, even before pressing, also steadily reduces. However, the experiment did reveal an interesting point. At extrusion temperatures below 70°C, i.e. 60 and 50°C, the % OIC before pressing rose dramatically, even above the values obtained at 140°C.

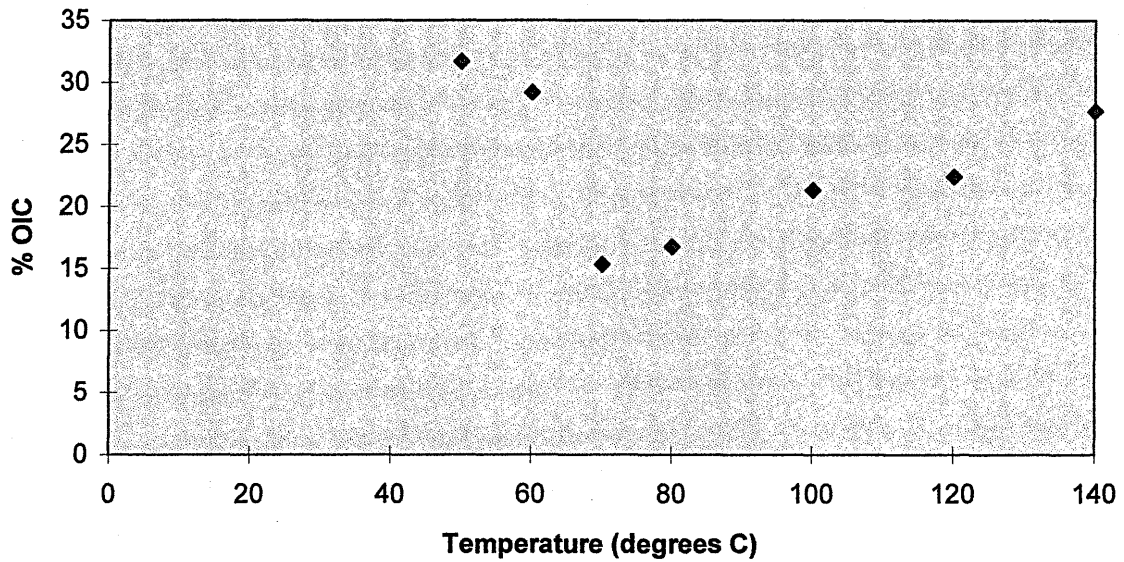


Figure 5.23 *Effect of barrel temperature on % OIC before pressing with extruder speed = 90 rev/min, die size = 5 mm and CR = 5:1*

A graph showing the results of the residual oil following extrusion and pressing is shown in Figure 5.24. The high % OIC from the extrusion runs at low temperature before pressing did not occur after the pressing stage. Figure 5.24 shows that the full range of temperatures follows the same polynomial trend as with the previous experiment. It would be interesting to carry out a milling defect and microscopy study of the 50 and 60°C samples and compare them to samples extruded at greater temperatures to try and understand why these high % OIC's occur.

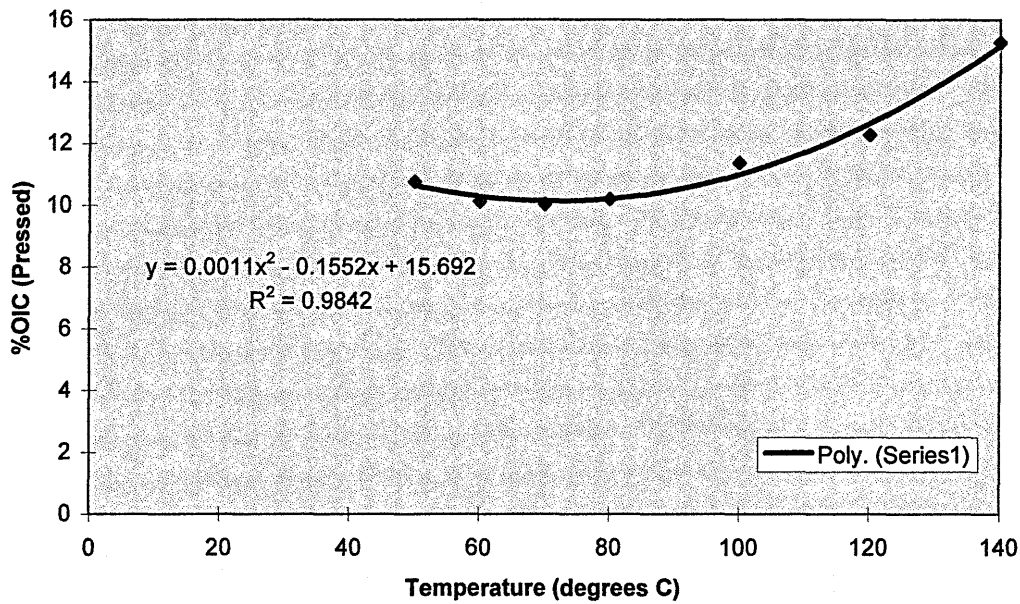


Figure 5.24 *Effect of barrel temperature on % OIC after pressing with extruder speed = 90 rev/min, die size = 5 mm and CR = 5:1*

5.9.3 Microscopy

A sample from each of the process conditions assessed in the experiment was taken for an analysis of the seed microstructure with light microscopy. The microscopy was carried out to assess the effect extrusion temperature has on the microstructure of extruded rapeseed over a greater temperature range than the previous experiment. The analysis of the microstructure may also give an insight as to why there was a sudden increase in the residual oil content following extrusion at processing temperatures below 70°C.

The microstructures of the seven samples extruded at 50, 60, 70, 80, 100, 120 and 140°C are shown in Figure 5.25. The results of the analysis of the microstructures follow the similar trend identified in the previous microscopy analysis on the effects of extrusion temperature on the seed microstructures with an increase in cell damage as the extrusion temperature is reduced. Plates *I*, *II*, *III* and *IV* (50, 60, 70 and 80°C respectively) are very similar and reveal little evidence of undamaged seed. Damaged cell structures become progressively less evident in Plates *V*, *VI* and *VII* (100, 120 and 140°C respectively) with Plate *VII* revealing large segments of intact seed cell structure, signified by the letter A.

The analysis of the microstructures did not reveal any major difference between the cell structures of rapeseed extruded at barrel temperatures 60°C and 70°C that would explain the large increase in % OIC at extruder barrel temperatures below 70°C identified in the residual oil analysis of the experiment shown in Figure 5.23.



Plate I Temperature 50 °C



Plate II Temperature 60 °C



Plate III Temperature 70 °C

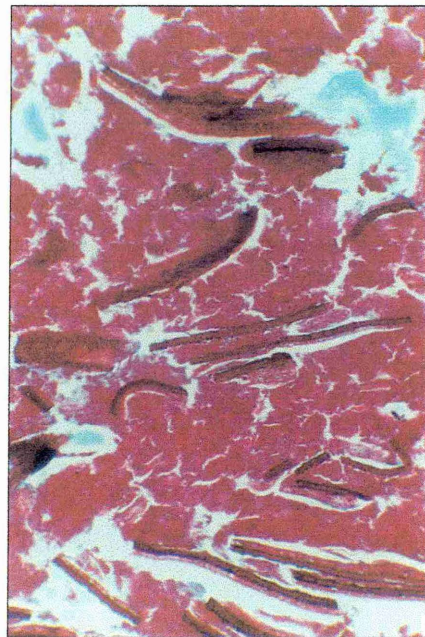
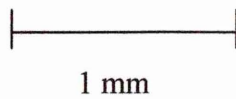


Plate IV Temperature 80 °C



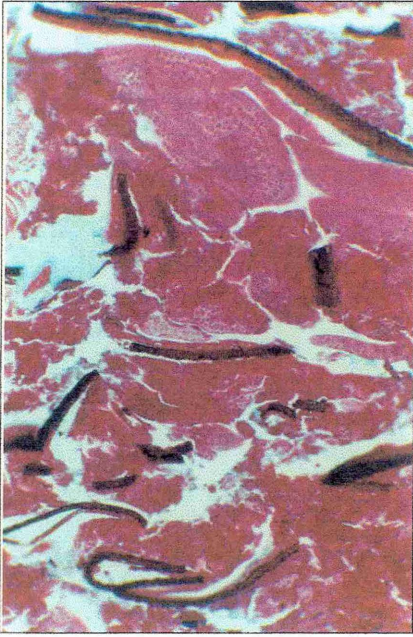


Plate V Temperature 100 °C

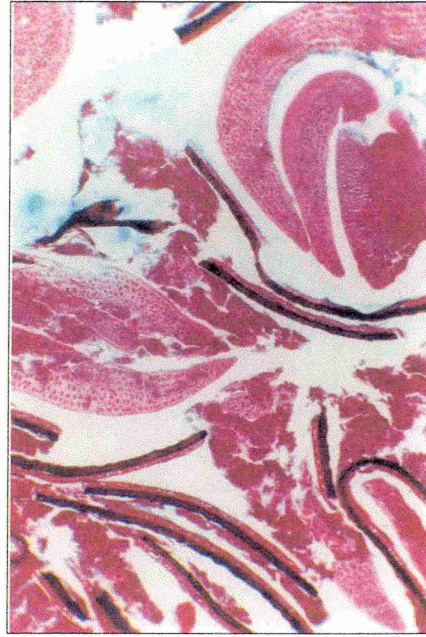


Plate VI Temperature 120 °C

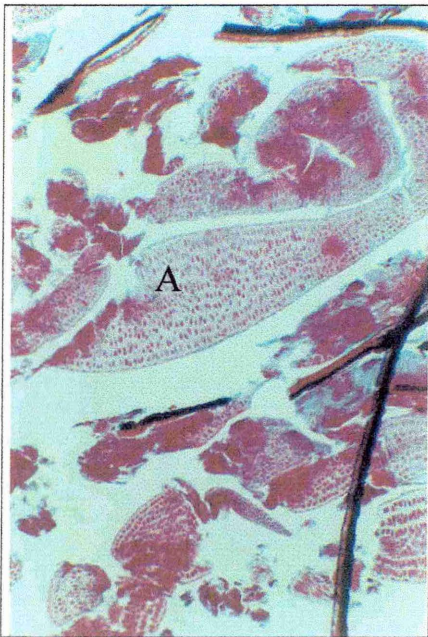


Plate VII Temperature 140 °C

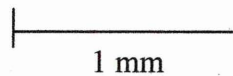


Figure 5.25 The effect extrusion temperature has on the microstructure of extruded rapeseed. The extruder operating conditions, screw speed 90 rev/min, die size 5 mm, screw compression ratio 5:1 and moisture content 7% were constant for the seven pictured samples

5.9.4 Milling Defect

A selection of extruded samples from both this experiment and experiment 3 were sent to a laboratory for an independent analysis of oil content and milling defect. The milling defect results were compared to the residual oil content results of the same samples as analysed at Cranfield University with the N.I.R. analyser. A graph showing the results of this comparison can be seen in Figure 5.26.

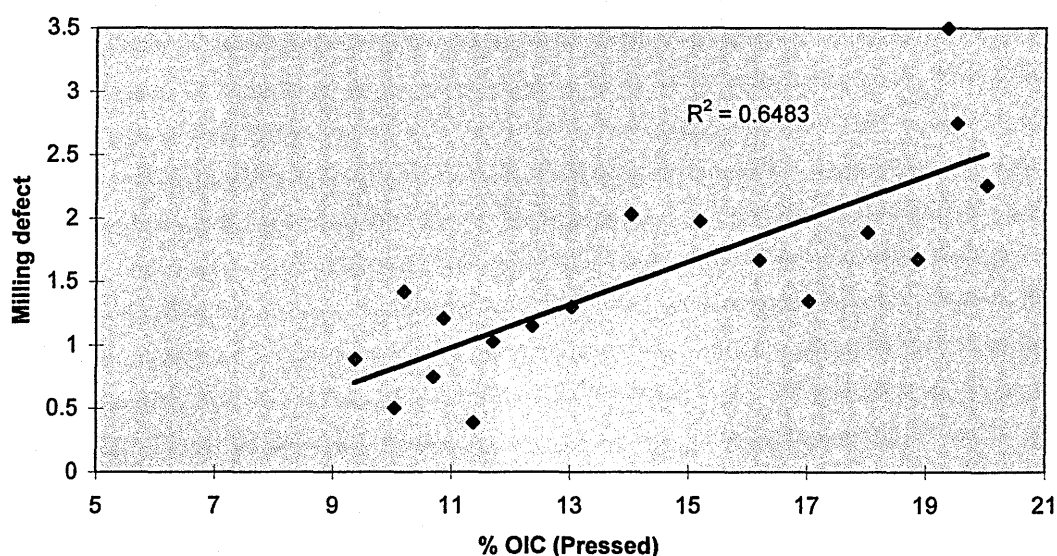


Figure 5.26 Relationship between the milling defect value of extruded rapeseed and the residual oil in cake after pressing.

It can be seen in Figure 5.26 that there is a positive linear correlation between the % OIC after pressing and the milling defect of the extruded samples. The correlation between % OIC after pressing and the milling defect of the extrudate confirms that the use of the ram press, as a tool to assess the performance of a preparation treatment, does relate to the standard test procedure used in the oil processing industry.

Another interesting point that can be drawn from Figure 5.26 is that the maximum milling defect value from the selection of samples analysed is approximately 3.5 and the lowest value 0.4. De Smet Rosedowns Ltd. state that the maximum milling defect value of between 3 and no greater than 5 would be expected in a prepared sample from a commercial processing plant. Figure 5.26 shows that all but one of the samples analysed have milling defect values below that which would be expected in a commercial processing plant.

Of the 18 samples analysed for milling defect shown in Figure 5.26, seven of the samples were taken from experiment 4 representing each of the 7 extrusion temperatures tested. Figure 5.27 shows the relationship between the extrusion temperature and the milling defect of the extruded sample.

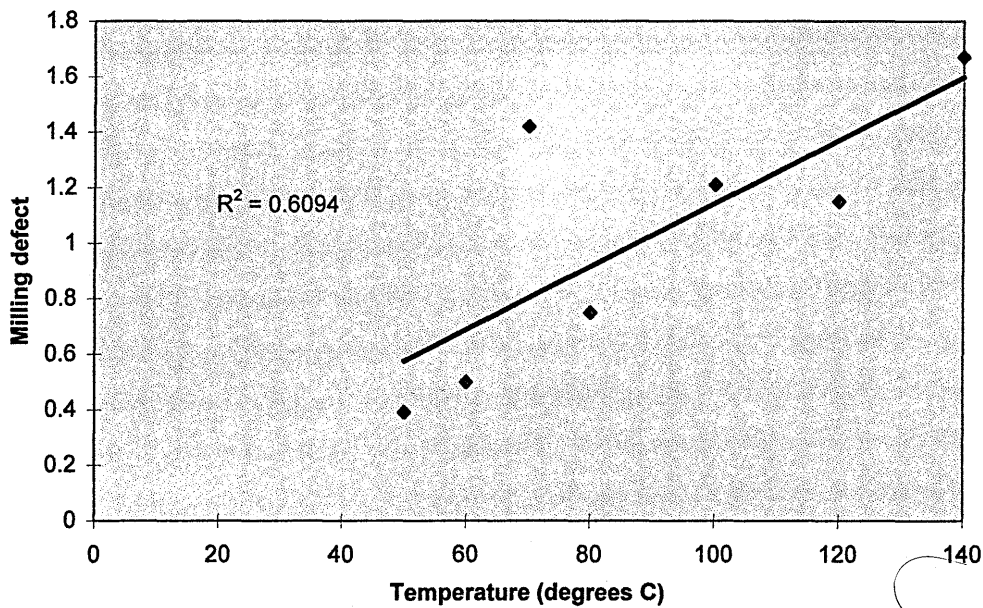


Figure 5.27 Effect extrusion temperature has on the milling defect value of extruded rapeseed.

It can be seen in Figure 5.27 that there is a positive linear relationship between extrusion temperatures and the milling defect of the extrudate. The milling defect analysis suggests that the performance of extrusion as a preparation treatment is enhanced as the process temperature is reduced.

5.10 Discussion

The laboratory scale extrusion experiments provided a great deal of information on what significance the individual process variables have on the preparation process. The findings from the experiments are discussed in the following section.

5.10.1 Moisture content

The rapeseed moisture content had a significant effect on the performance of extrusion as a preparation treatment. Results from experiment 1 show that by adjusting the rapeseed moisture content, ranging between 2.5 and 10%, with all other process variables remaining constant, the difference in the residual oil in cake following pressing was almost 11%.

The graphical representation of the results identifies a strong polynomial relationship between the process moisture content and residual oil after pressing. The highest % OIC was recorded at the lowest process moisture content assessed. The theoretical optimum process moisture content was calculated to be 7.5%. This is higher than the optimum recommended 4% MC stated by De Smet Rosedowns Ltd. for screw pressing rapeseed and could cause some problems with the screw press performance if the process were adopted. An advantage of being able to process rapeseed at 7.5% MC would be that it is within the optimum range of % MC that rapeseed is stored, therefore, no drying would be required prior to processing.

It is considered that rapeseed with a moisture content in excess of that assessed in the experiment would continue the upward trend in the percentage residual oil in the press cake identified in experiment 1. At a high moisture content the cells are turgid and wall strength is weak. The shear forces that occur through grinding, during the extrusion process, causes the whole structure to fail and mix together. This results in an extruded product with a paste like texture making it extremely difficult to extract the oil mechanically..

At the lower moisture contents assessed in the experiment the opposite effect to the cell structure will occur than at high moisture contents. The low moisture will result in low turgor pressure within the cells making the cell walls less rigid and more difficult to rupture. The absence of moisture in the seed will permit the cells to more readily deform producing granular particles that will become compacted through the high forces exerted on the seed during extrusion and pressing. Oil will become sealed in interstitial space within the seed matrix preventing its release. The cell structure together with the increased solid content, with a reduction of moisture, forms a compact matrix that will inhibit the percolation of oil.

5.10.2 Temperature

The extruder barrel temperature proved to be a significant factor in both the effectiveness of extrusion as a preparation treatment and on the power requirement of the process.

The effectiveness of the extrusion process to make oil available for expression diminished with an increase in temperature above a certain point. The critical temperature at which the effectiveness of extrusion was reduced does appear to be dependent on the screw compression ratio. The significance of extrusion temperature was demonstrated in experiments 2, 3 and 4 by the analysis of the residual oil in cake following extrusion and pressing and by an analysis of the microstructure and milling defect of the extruded rape seed.

In experiment 2, extrusion temperatures ranging from 115°C and 175°C at a compression ratio of 4:1 were assessed. An analysis of the microstructure clearly identified that as the temperature increased the percentage of cell rupturing during the extrusion process reduced.

An analysis of the residual oil in the extruded rapeseed identified that at lower extrusion temperatures a higher percentage of oil was released from the seed during the extrusion process. This is contrary to the findings from pressing trials and literature that suggests that pressing performance is enhanced at elevated temperatures when the oil is less viscous. The results from the experiment show that rupturing oil cells is of greater importance than lowering the viscosity of oil during the preparation stage of the extraction process. This supports findings from previous work that suggests that rupturing of cells during oil seed preparation is imperative if the efficiency of oil expression is to be maximised.

Experiment 3 assessed the effectiveness of extrusion at a lower range of temperatures than experiment 2, and also introduced the effects and relationships of other extrusion variables. As with experiment 2, of the range of temperatures assessed, from 80°C to 140°C, the residual oil in cake, this time following pressing, increased with an increase in temperature.

A relationship between extrusion temperature and screw compression ratio was identified and suggested that the optimum process temperature reduced with screw compression ratio. Of the four temperatures assessed in experiment 3, the lowest mean residual oil in cake after pressing occurred at 80°C, the lowest of the range of temperatures, at all 3 of the compression ratios assessed. A theoretical assessment suggested however that at screw compression ratios 3:1 and 4:1, the optimum processing temperature would be less than 80°C.

Experiment 4 assessed the effectiveness of the preparation process at lower extruder barrel temperatures than experiment 3. For this experiment seven barrel temperatures ranging from 50°C and 140°C were assessed. The extruder barrel would reach and maintain a temperature of approximately 70°C through mechanical energy alone and therefore needed to be cooled if lower extrusion temperatures were to be used. 50°C was the lowest temperature that could be maintained with the Brabender cooling system. The greater number of extrusion temperatures used in the experiment enabled the relationship between extrusion temperature and the residual oil after pressing to be identified with greater confidence.

The analysis of the residual oil following extrusion at the seven operating temperatures assessed did reveal a similar positive trend as was identified in experiment 2 with a decrease in the residual oil in extruded rape seed with a reduction in the extrusion temperature. However, at temperatures below 70°C the residual oil in the extruded rape seed did increase dramatically to a figure above that obtained at 140°C, the maximum extrusion temperature assessed in the experiment. The analysis of the microstructure did not reveal any significant differences between rapeseed samples extruded at temperatures 50, 60 and 70°C therefore it is considered that the justification for the rapid increase in the residual oil is due to the low viscosity of the oil at the low extrusion temperatures prohibiting the release of oil from the seed matrix.

As with experiment 3, the results from experiment 4 revealed a strong polynomial relationship between extrusion temperature and residual oil after pressing, again with the lowest residual oil after pressing following extrusion at the lowest temperature range.

The analysis of the extruded seed microstructure of samples from each of the seven extrusion temperatures assessed in experiment 4 did reveal that at high extrusion temperatures, as in experiment 2, a large number of non-ruptured oil cells were still remaining in the seed structure. As the extrusion temperature was reduced, the number of non-ruptured oil cells were also reduced. There was little difference in the microstructures of the extruded seed at extrusion temperatures 80, 70, 60 and 50°C all of which showed little evidence of intact oil cells remaining in the seed structure.

The analysis of the microstructures of extruded rapeseed in experiments 2, 3 and 4 all reveal that extrusion process is more effective at grinding the rapeseed and damaging the cell structure at lower extrusion temperatures. It is considered that the reason for increased damage to the cell structure at lower temperatures is that at low extrusion temperatures the seed is more brittle and more easily broken by the grinding processes. At higher extrusion temperatures the seed will become more malleable, this allowing the seed to deform without breaking during the grinding process within the extruder.

The analysis of the milling defect revealed that, as with the residual oil analysis, the effectiveness of extrusion as a preparation treatment was less at the higher temperature range. However, unlike the residual oil analysis, the relationship between extruder barrel temperature and the milling defect of the extruded rapeseed revealed a positive linear correlation.

An encouraging point gained from experiment 4 was the low milling defect values obtained from the extruded rapeseed. It has been stated earlier that, for a prepared sample in commercial processing plant, a milling defect value of between 3 and no greater than 5 would be expected. The highest milling defect value from experiment 4 was 1.7, just over half of the lowest figure that would be expected in a commercial processing plant.

The barrel temperature also proved to significantly effect the power requirement of the preparation process. Results from experiment 3 suggested that the power requirement at extrusion temperature of 140°C was significantly greater than at the lower temperatures examined. The reason for the increased power requirement at the high extrusion temperature is that to maintain the high extruder barrel temperature during the extrusion process, it is necessary for the barrel heaters to be switched on virtually constantly. At lower processing temperatures the length of time that the barrel heaters are required to be switched on to maintain a constant processing temperature is reduced.

5.10.3 Compression Ratio

The analysis of the results from experiment 3 identified the screw compression ratio as being a significant factor in the effectiveness of extrusion as a preparation treatment for rapeseed. The results suggested that the residual oil in the press cake is significantly lower following extrusion with a screw compression ratio of 5:1 than screw compression ratios of 3:1 or 4:1. However, a relationship between extrusion temperature and compression ratio has already been discussed stating that higher compression ratios were more effective at higher temperatures, at 80°C there is no significant difference in the performance at different compression ratios, and projected figures suggested that lower compression ratios would be more effective at lower temperatures.

The justification for the results of the residual oil analysis of the press cake and the analysis of the seed microstructure following extrusion, identifying that using an extruder screw with a compression ratio of 5:1 is more effective as a preparation treatment at high extrusion temperatures than with a screw compression ratio of 4:1 or 3:1 is again due to the malleability of the seed at elevated temperatures.

The increased deformation characteristics of the seed at elevated temperatures prevent the seed from breaking at lower compression ratios. At elevated temperatures a greater force needs to be exerted on the seed to damage the seed cell structure, this is achieved by increasing the screw compression ratio. At lower extrusion temperatures the seed is less able to deform reducing the force required to damage the seed cell structure. It is therefore less imperative to have a 5:1 screw compression ratio at low extrusion temperatures as a compression ratio of 3:1 will exert sufficient force on the seed damage the seed cell structure.

The extrusion temperatures assessed in experiment 3 ranged from 80°C and 140°C. The temperature range does bias the significance of the compression ratio in favour of the higher compression ratios, in this case 5:1. This fact should be considered when ascertaining the optimum processing conditions that will achieve maximum preparation efficiency.

The extruder screw compression ratio also significantly effects the power requirement of the extrusion process. The results from experiment 3 identified that the power requirement was significantly greater while extruding with a 4:1 and a 5:1 screw compression ratio than with a 3:1 compression ratio. The results also revealed that there is no difference in power requirement between extruding at compression ratios 4:1 or 5:1.

A reduction in the power requirement of the extruder would be expected as the compression ratio of the screw is reduced. The screw in the extruder operates by the same principle as described for a press screw continually shearing and exerting radial pressure on the rapeseed through volumetric compression. As the compression ratio is increased, so is the radial pressure on the seed. The increase in internal pressure will increase the load on the extruder motor driving the screw.

The theory explaining why the power requirement is less at low screw compression ratio does not explain why there is no difference between the extruder power requirement at screw compression ratios 4:1 and 5:1. A relationship between compression ratio and another process variable that is significant to the power requirement, or, if the compression ratio was significant to the throughput of the extruder, a figure used in the calculation of the power requirement, could both help explain why there is no change in the power requirement between screw compression ratios 4:1 and 5:1. As neither of the above factors apply no explanation as to why there is no change in extrusion power requirement between screw compression ratios 4:1 and 5:1 has been given.

5.10.4 Die size

The die size proved to be a significant variable in the effectiveness of the extrusion process as a preparation treatment for pressing. An analysis of the results from experiment 3 revealed that the effectiveness of the extrusion process was enhanced with a smaller diameter die. The analysis revealed that with a 5 mm die the effectiveness of the preparation treatment was significantly better than with a 7 mm diameter die. The analysis also identified that there is no significant difference in the effectiveness of the extrusion process in using a 5 mm or 6 mm die, or, a 6 mm or a 7 mm die. The 1 mm incremental change in the die size was not enough to affect the performance of the extruder.

A possible explanation of why a smaller die size improves the effectiveness of the preparation treatment is that an increase in pressure exerted on extrusion material behind the die, caused by a restriction in the flow of the material, will assist in the process of rupturing the oil cells increasing the availability of the oil.

Individually the die size did not have any significant effect on either the power requirement of the extrusion process or on the throughput of the extruder.

5.10.5 Screw Speed

The extruder screw speed proved to be a significant process variable in the effectiveness of the extrusion process in the preparation of rapeseed. An analysis of the results from experiment 3 show that the lowest % residual oil after pressing was achieved from rapeseed extruded at a screw speed of 90 rev/min. The residual oil was significantly lower than in the press cake following extrusion at 120 and 150 rev/min. There was no difference in the effectiveness of the extrusion process at screw speed 120 and 150 rev/min.

A possible reason why the slower screw speed proved more effective than the higher screw speeds is that less rotational slippage of the rapeseed may occur at the lower speeds. Less rotational slippage of the rapeseed during extrusion will increase the radial pressure subjected to the seed.

The extruder screw speed also has a significant effect on the extruder power requirement and the throughput of the machine. At 150 rev/min, the maximum screw speed examined in the experiments, the power requirement per mass of seed extruded was greater than at 90 or 120 rev/min. There was no significant difference in the power requirement between screw speeds 90 rpm and 120 rpm. The increase in power requirement at greater screw speeds would be expected due to the increased load on the extruder drive motor.

The throughput of the extruder however significantly improves as the screw speed is increased. It has been shown that the extruder screw speed, as an individual process variable, is significant to the effectiveness of the preparation, the power requirement and throughput of the extruder. The residual oil in the press cake was lower after extruding at 90 rpm than at 120 and 150 rev/min, the power requirement was lower at 90 and 120 rev/min than at 150 rev/min, and the throughput of the machine increased with each incremental increase in the screw speed.

The optimum extrusion screw speed has been identified as being different for each of the 3 process factors i.e. the residual oil in press cake, the power requirement and the machine throughput. Before an overall optimum screw speed setting can be identified, the three process factors would have to be prioritised to identify which is the most important to the oil processor. This is likely to vary between processors depending on extraction plant location and economic variations. For example, in areas where energy is at a premium then the power requirement could feature as the main criteria when selecting a process condition. In an economic situation where the cost of oilseed or selling price of the oil is of a premium, then the residual oil could feature as the main criteria.

5.11 Conclusion

1. The results from the pilot scale experiments suggest that extrusion technology does have the potential to provide an effective preparation treatment for the mechanical extraction of oil from rapeseed.
2. Rapeseed moisture content, extruder barrel temperature, screw speed, die size and compression ratio are all significant processing variables for the preparation treatment of rape seed with an extruder.
3. Analysis of the microstructure of extruded rape seed identified the extruder barrel temperature as a significant factor in the ability of the extrusion process to damage the rapeseed cell structure. Greatest damage to the cell structure occurred at barrel temperatures below 100°C
4. At a barrel temperature of 80°C, no advantage to the preparation treatment is gained from increasing the screw compression ratio above 3:1.
5. The optimum Brabender extruder operating variables identified in the pilot trials that achieve the most effective preparation treatment are barrel temperature no greater than 80°C, a screw compression ratio of 3:1, a screw speed no greater than 90 rev/min and a die size between 5 and 6 mm diameter. These process variables will also provide the lowest extruder power requirement, however, to achieve maximum machine throughput the screw speed must be increased to at least 150 rev/min.

6. LARGE SCALE EXTRUSION EXPERIMENTS

6.1 Introduction

The set of large scale extrusion experiments designed to determine the processing variables or combination of variables that are significant to the preparation process, and to ascertain at what range the variables most enhance the oil extraction process are described and discussed within this chapter. The aims, objectives and methodology of the set of experiments are detailed along with a description of the equipment used. The results of each experiment are presented, analysed and discussed in detail at the end of the chapter.

6.2 Aim

To determine the optimum operating conditions of a large scale extrusion cooker as a preparation treatment prior to the mechanical extraction of oil from rapeseed and compare this process with traditional preparation treatments. The effect that individual extruder operating variables have on the preparation process are also to be assessed.

6.3 Objectives

- Design and implement a set of experiments using a single screw Almex extrusion cooker to obtain a number of samples from a range of operating variables.
- Record the oil extraction efficiency and throughput for each operating condition and study the effect the preparation treatment has on the microstructure of the rape seed.

- Analyse the results to determine the optimum extruder operating conditions as a preparation for the efficient extraction of rapeseed oil and the effects individual operating variables have on this process.

6.4 Methodology

- Design a set of experiments to enable the full range of each operating condition to be assessed.
- Conduct the experiments to obtain extruded samples and record required operating data, and then press the extrudate in a screw press to assess the oil extraction efficiency.
- Prepare a sample simulating traditional preparation methods and test for oil extraction efficiency.
- Analyse the results of the experiment to determine the optimum operating conditions and the effect the individual variables have on the process. Compare the performance of the extruder as a preparation process with the traditional preparation process.

6.5 Equipment

The following section identifies and discusses the equipment used for the large scale extrusion experiments.

6.5.1 Extruder

6.5.1.1 *Extruder specification*

The extruder used for the set of experiments was an Almex single screw cooker-extruder and is powered with a 11 kW electric motor.

The extruder barrel is fluted to prevent the feed material rotating with screw during the extrusion process. As with screw pressing, rotational slippage of the material within the barrel increases the residence time of the material being extruded, in turn reducing the throughput of the machine. Excessive rotational slippage can stop throughput completely. The barrel is insulated along its length and can be heated in the final half of the barrel length with electric heaters. The barrel can be cooled along the full length of the barrel to approximately -10°C with the aid of a Tricool Trim 30 refrigeration unit circulating cooling fluid around the barrel. The Almex extruder and refrigeration unit used in the experiments are shown in Figure 6.1

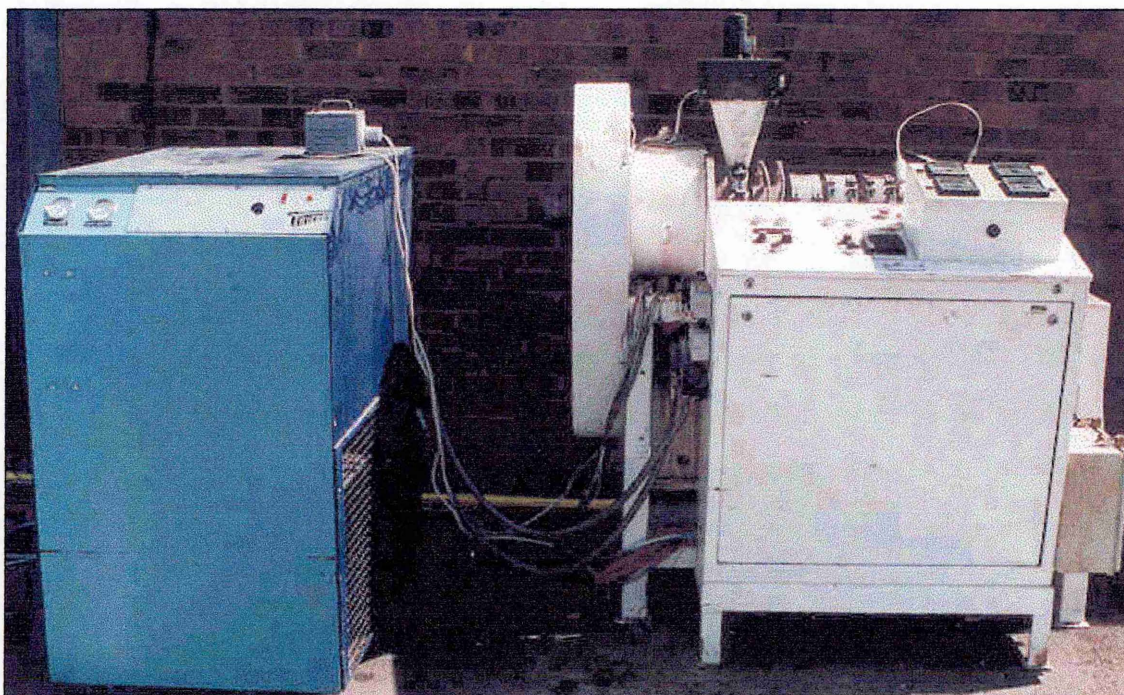


Figure 6.1 Almex single screw extruder and refrigeration unit used for the large scale extrusion experiments

The extruder screws available with the extruder are a chromed continuous screw type, 48 mm in diameter and with a screw length of 600 mm. A range of screw compression ratios from 1:1 up to 3:1 are available with the machine.

The extrusion operating variables for the Almex detailed below.

Compression ratio	1:1, 1.5:1, 2:1, and 3:1
Operating Temperature	maximum 200°C (variable)
Die size	5 mm, 7 mm and 9 mm round, various slotted
Screw speed	200 rev/min (variable speed)
Operating Pressures	(adjusted using die size and worm speed)
Shear	(adjusted using die size and worm speed)
Residence time	(adjusted using die size and worm speed)

6.5.1.2 *Extruder operation*

A number of pilot trials were completed prior to the main set of experimentation, firstly, to ensure that the Almex extruder was suitable for extruding rapeseed, and secondly, to identify the range of each individual operational variable that would enable the extruder to operate consistently at a reasonable throughput and produce a satisfactory product, before deciding on a range of operating variables to be used in the set of experiments. The major findings from the pilot trials are highlighted below.

- Oil saturation - initial trials with the Almex extruder, as with the Brabender, highlighted a problem of oil saturation after only a few minutes of operation. Oil saturation reduces the axial movement of the feed material in turn reducing the throughput of the extruder. The pressure gradient within the extruder barrel forced the free oil, against the flow of the solid material, towards the feed end of the extruder and eventually up into the feed hopper. The oil saturation made the throughput of extruder inconsistent and eventually, depending on operational variables, stopped throughput completely.

To overcome the saturation problem, a 13 mm diameter oil drain was drilled at the feed end of the extruder to remove the free oil from barrel. The drain had a wire filter to prevent rape seed escaping from the barrel. A combination of the oil drain and the addition of a positive feed screw auger fitted to the feed hopper alleviated the saturation problem.

- Temperature - the extruder operated successfully over the full available temperature range.
- Compression Ratio - it was found that a large number of whole seeds were present in the extrudate when using the 1:1 and 2:1 compression ratio screws, therefore it was decided to use 3:1 compression ratio screw for the set of experiments.

- **Die Size** - the throughput of the extruder was inconsistent and prone to blocking at the lower die sizes. The slotted dies also caused the machine to block.
- **Screw Speed** - the Brabender trials revealed that the throughput of the extruder was dependent on the extruder screw speed. For this set of experiments it was considered necessary to achieve the maximum possible throughput from the extruder in order to match as close as possible the throughput of the screw press being used for the experiments. The maximum screw speed of the extruder has previously been stated as 200rev/min. It was however discovered that, at this speed, the throughput of the machine became inconsistent and eventually stopped completely. The maximum screw speed at which the throughput of the machine was consistent was 120 rev/min.

6.5.2 Screw press

The press used for the experimentation was a prototype DeSmet Rosedowns Ltd. Mini 100 screw press designed for small scale oilseed processing and can operate on most seeds. A sketch of the press can be seen in Figure 6.2.

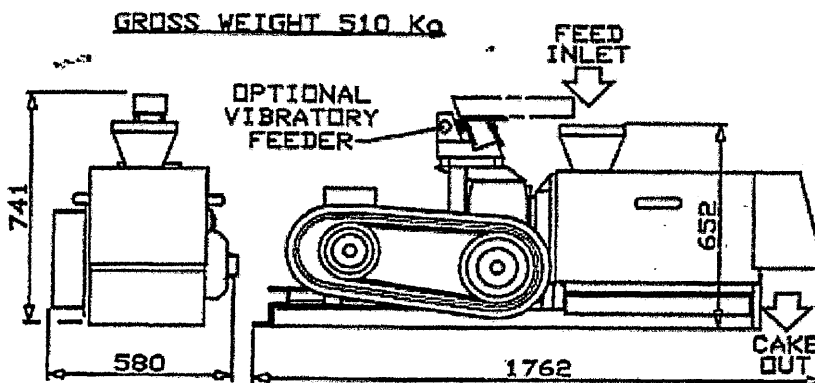


Figure 6.2 Sketch drawing of the De Smet Rosedowns Ltd. screw press used for the large scale extrusion experiments

- The Mini 100 screw press normally has a nominal capacity of approximately 100 kg per hour, however, for these experiments the speed reduction was increased reducing the throughput to approximately 50 kg per hour, closer to that of the Almex extruder. The press is claimed by the manufacturer to achieve an oil yield of up to 73% on a cold pressing duty (based upon initial oil level in seed), this yield can be increased by second pressing the oilseed.
- The press is fitted with a split cage drainage barrel with a 100 mm diameter bore and 560 mm in length. The worm assembly is made up of individual worms and humps mounted on a worm shaft. For the experiments the clearance between humps and drainage cage were 3 mm and 1 mm, the later determining the thickness of the press cake.

The power source for the Mini 100 was a 7.5 kW, 3 phase, electric motor. Speed reduction is achieved by a v-belt drive and combined helical gears and worm gear.

Prior to each experimental run the press was operated for between 0.5 and 1 hour on rapeseed, or extrudate and press cake from previous runs, to ensure that the press cage and worm assembly had reached a uniform and stabilised operating temperature producing a press cake at approximately 80°C.

6.6 Experiment 1. The effect extrusion operating variables have on the efficiency of the process as a preparation treatment.

Experiment 1 is designed to assess if the results gained from the smaller scaled Brabender extruder experiments, which identified the extruder barrel temperature as of significant importance to the performance of extrusion as a preparation treatment of rapeseed for the pressing of oil, were comparable when scaled up closer to that of a commercial scale.

The refrigeration unit available with the Almex extruder enabled a wider range of barrel temperatures to be assessed than was possible with the Brabender trials. The experiment also compares the performance of extrusion, as a preparation treatment for pressing, with more conventional preparation treatments used in the oil processing industry.

6.6.1 Experiment variables

The experiment assessed 5 extrusion treatments, 3 non-extrusion treatments and an untreated sample. Each treatment was double pressed with a mini 100 screw press. The residual oil, milling defect and microstructures were recorded and analysed as in the Brabender trials.

The extruder operating variables and rapeseed moisture content chosen for the experiment are detailed in Table 6.1

Table 6.1 *Process variables for the large scale extrusion experiment 1. The effect extrusion operating variables have on the efficiency of the process as a preparation treatment.*

Rape seed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rev/min)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
7.5	0 40 80 120 150	120	9	3:1	
1	5	1	1	1	5

The three non-extrusion preparation treatments used for the experiment were cooking, milling and milling and cooking combined.

To simulate commercial rapeseed conditioning or cooking, 7 trays sized 440 mm x 280 mm, each containing 1.5 kg of rape seed, were placed in an electric fan assisted oven at 90°C for 1 hour. Following conditioning the rapeseed was rapidly transported to the preheated screw press for pressing. The conditioned seed entered the press at approximately 75°C.

To simulate flaking the rapeseed was rolled in a roller mill. The milled seed contained no whole seed.

To simulate the flaking and seed conditioning, used in conventional commercial preparation of rapeseed for pressing, the seed was first milled in a roller mill and then cooked in a fan assisted electric oven as described above.

The untreated rapeseed was pressed directly from the grain store.

The experimental procedure was of a completely randomised design with each preparation treatment replicated three times and all samples double pressed.

6.6.2 Analysis of results

A statistical analysis of the experiment data was carried out to assess the significance that the extrusion temperature has on the oil extraction efficiency of the process, together with a comparison between preparation of rapeseed with the extruder and that with conventional preparation treatment. The residual analysis of the experimental data showed a normal distribution with no regular pattern.

An examination of the seed microstructure and a milling defect analysis were carried out on a sample of the preparation treatments assessed.

6.6.2.1 Residual oil analysis

An analysis of the residual oil was carried out following extrusion, the first press and the second press on the extruded samples in the experiment. A full set of results and statistical analysis is shown in Appendix J

The % OIC of the extruded seed prior to pressing follows a similar pattern to the previous laboratory scale Brabender extrusion experiments. Figure 6.3 shows that as the extrusion temperature decreases the oil released during the process increases until a critical temperature is reached. Below the critical processing temperature virtually no oil is released from the rapeseed resulting in the residual oil in the extruded rapeseed near that of the initial oil content of the rapeseed. It can be seen in Figure 6.3 that the increase in % OIC occurs at a temperature below 40°C.

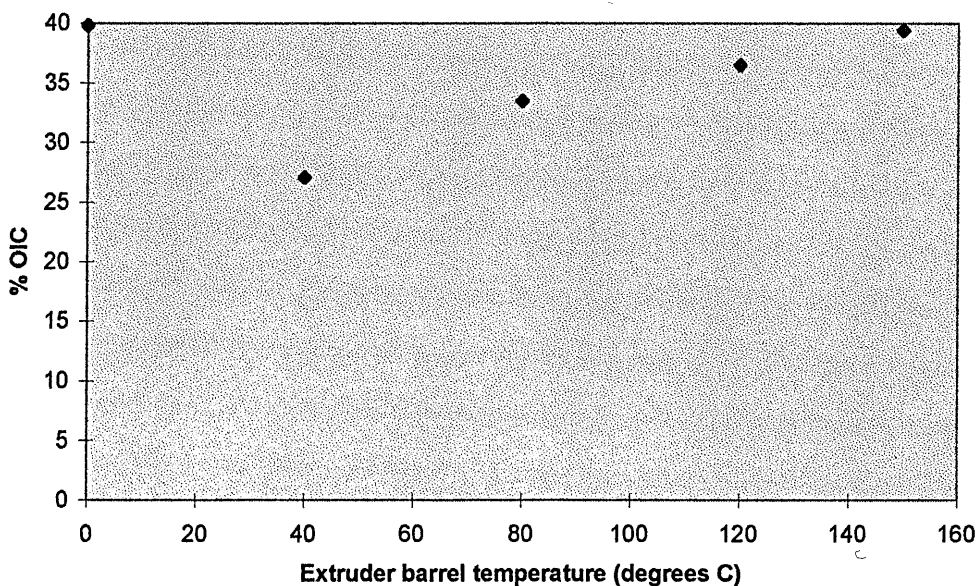


Figure 6.3 The effect extrusion temperature has on % OIC following extrusion.

The mean % OIC following extrusion and a single press for each of the extrusion treatments can be seen in Figure 6.4. The figure shows that the results of the residual oil analysis for the five extrusion treatments did not follow any statistical correlation. The mean % OIC following extrusion at 150°C and a single press was 13.53%, at 120°C the mean % OIC increases to 14.81%. The mean % OIC then decreases, reaching a minimum of 12.64% following extrusion at 40°C. The mean % OIC increases at extrusion temperatures below 40°C up to 13.64% following extrusion at 0°C. The standard deviations of the means for analysis of the residual oils following extrusion and a single press does reveal some inconsistency between replications at extrusion temperatures of 80 and 120°C.

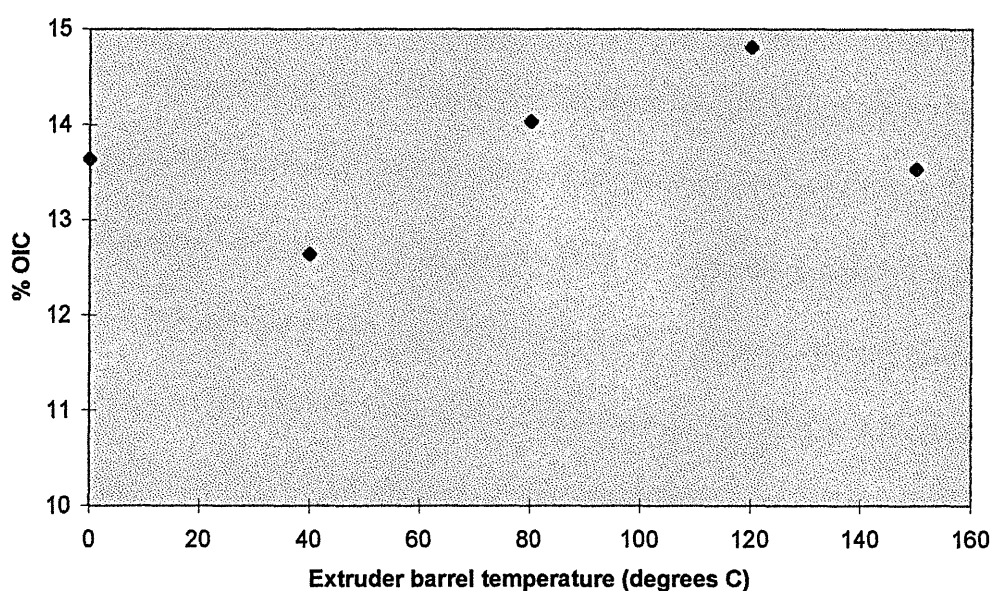


Figure 6.4 *The mean % OIC following extrusion at a range of processing temperatures and a single press*

The mean % OIC following extrusion and a double press for each of the extrusion treatments can be seen in Figure 6.5. The results of the % OIC analysis following extrusion and a double press were considerably more consistent than those following a

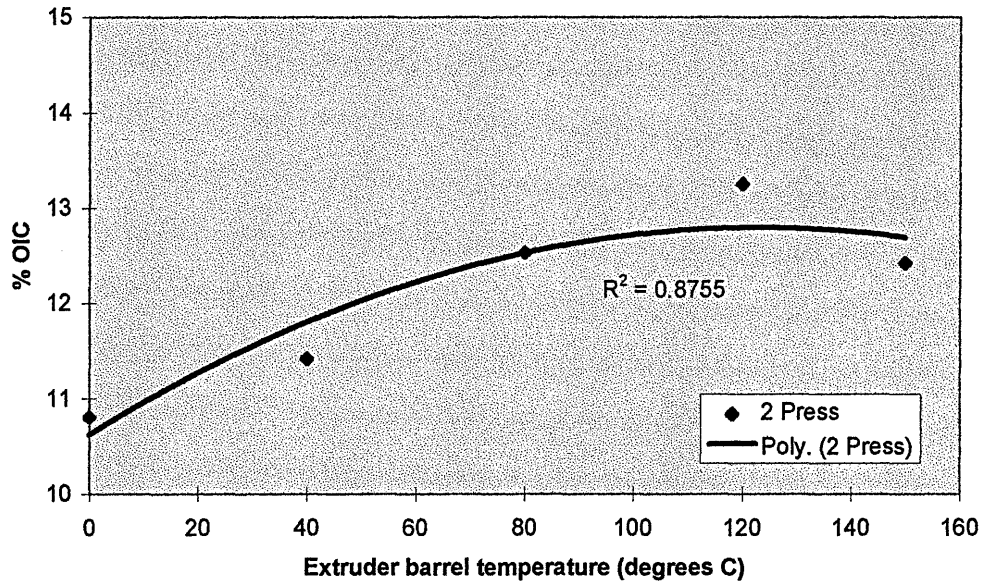


Figure 6.5 The effect extrusion temperature has on the % OIC following a double press.

The graph, Figure 6.5, shows the extruder barrel processing temperature / % OIC (double pressed) curve has a strong polynomial trend with R^2 value of the 0.8755. The mean % OIC following extrusion at 150°C is 12.42%, the mean % OIC increases as the extrusion temperature is reduced peaking at a mean % OIC of 13.25% following extrusion at 120°C. The mean % OIC then decreases with a reduction in the extrusion processing temperature to a mean % OIC of 10.81% at 0°C. The results of the analysis of residual oil in cake following a double press follow a similar trend as the Brabender laboratory scale experiments in that a greater process efficiency is achieved at lower extrusion temperatures.

A table of means and standard deviations for the non-extrusion preparation treatments following a single and double press can be seen in Appendix J.

The results of the analysis of the mean % OIC following the non-extrusion preparation treatments and a single press is shown in Figure 6.6.



Figure 6.6 *The effect the non-extrusion preparation treatments have on mean % OIC following a single press.*

The single pressed untreated seed, has a mean % OIC of 15.36%, this figure is lower than was achieved with the cooked seed which, following a single press, has a mean % OIC of 16.3%. The milled sample did enhance the performance of the press compared to the untreated seed with a mean % OIC of 14.75%. The best press performance, of the non-extruded samples following a single press, was however achieved with the conventional commercial preparation treatment of milling and cooking having a mean % OIC of 12.42%. It should be noted that during the pressing stage of the conventional milled and cooked treatments, the throughput of the press was low and a high amount of foots were forced through the press drainage gaps and little free running oil was expressed. Due to the low throughput a second press of the milled and cooked sample was not undertaken.

The results of the analysis of the mean % OIC following the non-extrusion preparation treatments and a double press are shown in Figure 6.7.

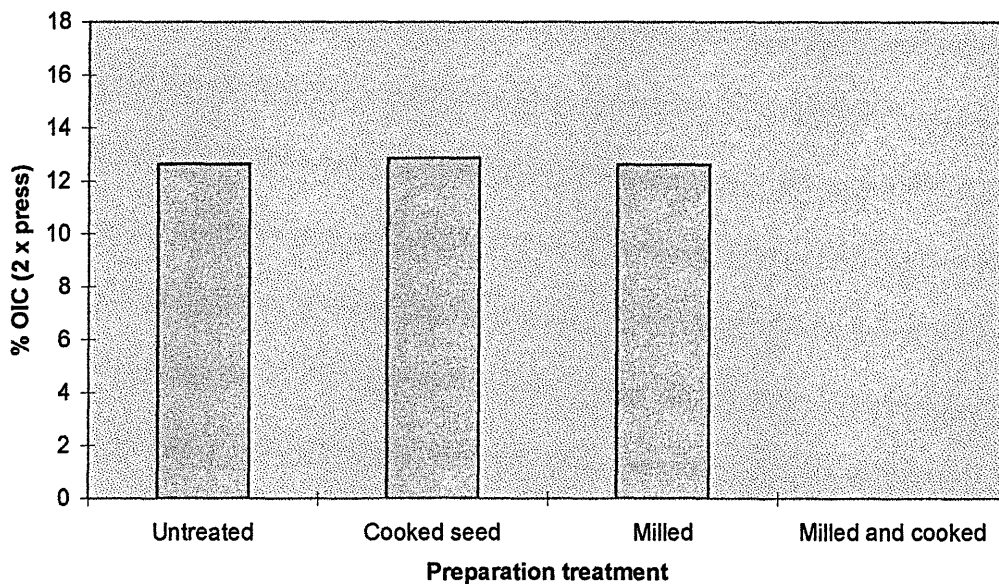


Figure 6.7 The effect the non-extrusion preparation treatments have on mean % OIC following a double press. (No data was available for the milled and cooked treatment).

The chart shows that there is little difference in the efficiency of oil extraction following a double press with untreated, cooked or milled seed. The mean % OIC of the three non-extrusion treatments following a double press are 12.64%, 12.86% and 12.62% respectively. One of the milled treatments produced excessive foots during the second press, therefore, no data for the residual oil in cake analysis, following a second press, is available for this sample.

The results of the analysis of the mean % OIC following all of the preparation treatments assessed in the experiment both single and double pressed are shown in Figure 6.8.

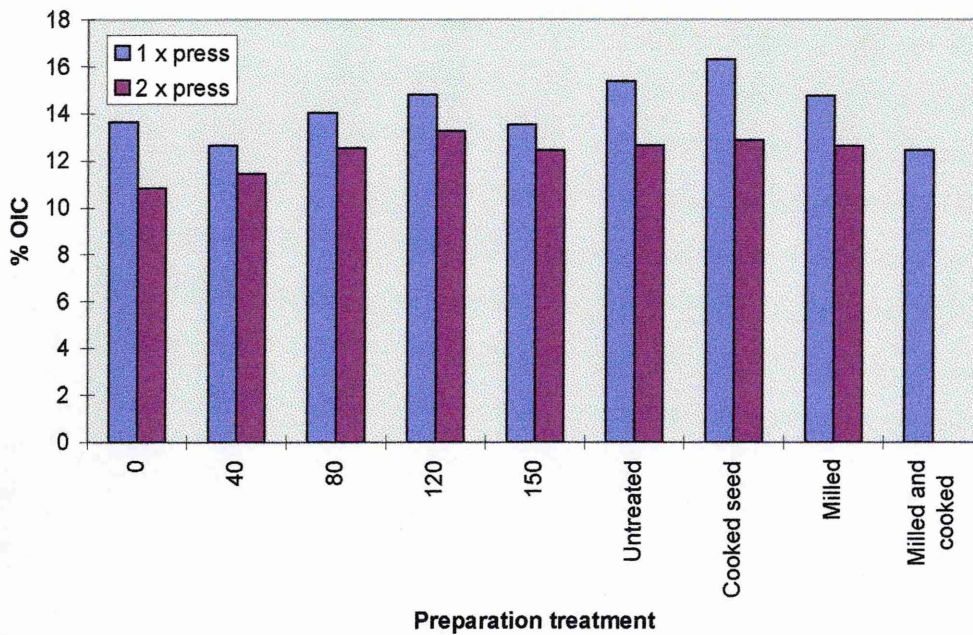


Figure 6.8 The effect various preparation treatments have on % OIC following a single and double press. Note: Numerals on preparation treatment axis represents extruder barrel temperature ($^{\circ}\text{C}$)

An analysis of variance of the residual oil analysis results for all of the preparation treatments assessed in the experiment was calculated following both single and double pressing. The analysis of variance was calculated to identify if there is any significant differences in the performance of the pressing procedure following different preparation treatments assessed. The ANOVA tables and least significant difference (l.s.d.) calculations for both sets of results can be seen in Appendix J. The F probabilities of the analysis of variance for both single and double pressing identified that the method of preparation does significantly effect the performance of the subsequent pressing procedure.

The calculation of the l.s.d. for the mean % OIC of the preparation treatments following a single press reveal that the conventional preparation treatment of milling and cooking, and extruding at a barrel temperature of 40°C are significantly more effective than the untreated, cooked, and milled treatment, and the extrusion treatment extruded at a barrel temperature of 120°C. The l.s.d. calculation also reveals that there is no significant difference between the conventional milled and cooked treatment, and the extrusion treatments extruded at barrel temperatures 0, 40, 80 and 150°C.

The calculation of the l.s.d. for the mean % OIC of the preparation treatments following a double press revealed that there was no significant difference between the extrusion preparation treatments extruding at barrel temperatures of 0 and 40°C. The analysis also shows that these two preparation treatments are significantly more effective than the other preparation treatments investigated within this experiment.

6.6.2.2 Extruder Throughput

The throughput of the Almex extruder, at each of the five extruder process conditions used in the experiment, was calculated to see what effect the extrusion temperature has on the throughput of the machine.

A sample of the extruded rapeseed, from each of the process conditions, was collected from the extruder over a recorded period of time and weighed. Following an analysis of moisture content and the residual oil of the extruded rapeseed the machine throughput for each process condition could be calculated. The throughput of the Almex extruder at each of the extrusion temperatures assessed can be seen in Figure 6.9

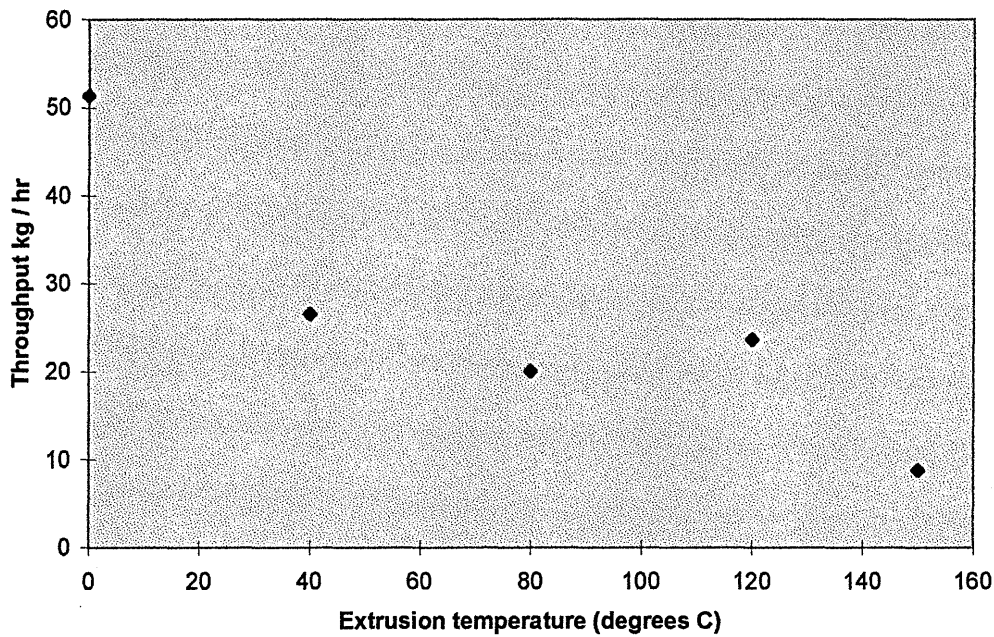


Figure 6.9 *The effect extrusion temperature has on the throughput of the Almex extruder*

The results of the throughput analysis reveal that at extrusion temperatures 40°C, 80°C and 120°C the throughputs are similar at 26.55, 20.07 and 23.63 kg/hr respectively. There is however a large difference in the throughput of the extruder at the extreme temperature ranges assessed in the experiment. At an extrusion temperature of 150°C, the throughput of the extruder was only 8.80 kg/hr, and at 0°C the throughput was calculated at 51.37 kg/hr.

6.6.2.3 Microscopy

A sample from each of the process conditions assessed in the experiment was taken for an analysis of the seed microstructure with light microscopy. The microscopy was carried out to assess what effect a wide range of extrusion temperatures has on the microstructure of rapeseed extruded with the Almex extruder. The analysis of the microstructures will also permit a comparison between the laboratory scale Brabender extruder and the large scaled Almex extruder's effectiveness at destroying the rapeseed cell structure during the extrusion process.

The microstructures of the five samples extruded at 0, 40, 80, 120 and 150°C are shown in Figure 6.10. The greatest damage to the seed cell structure is evident in Plate II, at an extrusion temperature of 40°C. The second highest percentage of cell damage is seen in plate III at an extrusion temperature of 80°C. Both plates II and III do reveal extensive cell damage. Plates I (0°C), IV (120°C) and to a lesser extent Plate V (150 °C) all reveal large segments of undamaged cell structure, this is particularly evident in Plate I.

The analysis of the microstructure of the rapeseed extruded with the Almex extruder does follow a similar trend to the microscopy carried out on samples extruded with the smaller laboratory scaled Brabender extruder discussed in Chapter 5. The greatest damage to the seed cell structure occurred at temperatures below 120°C in both the Almex and Brabender trials, however, in the analysis of the Almex trials a reduction in the efficiency of the process to damage the cell structure at the extreme low temperatures, below that in the range of temperatures in the initial Brabender extruder trials, was discovered.

A comparison in the microstructures of samples extruded with the two extruders reveals that the extent of the cell damage, following extrusion at similar operating conditions, is generally greater with the Brabender extruder than with the larger Almex extruder.

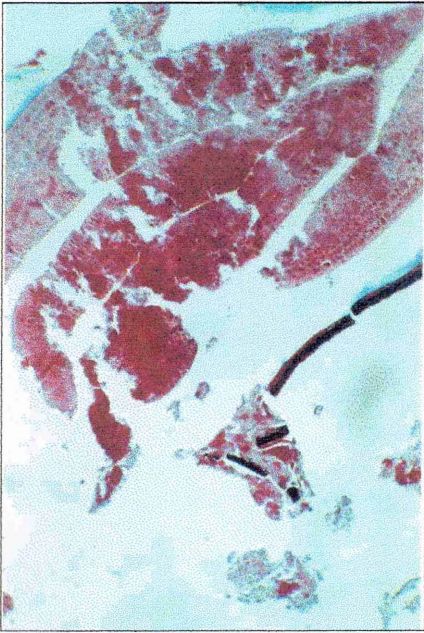


Plate I Temperature 0 °C



Plate II Temperature 40 °C



Plate III Temperature 80 °C

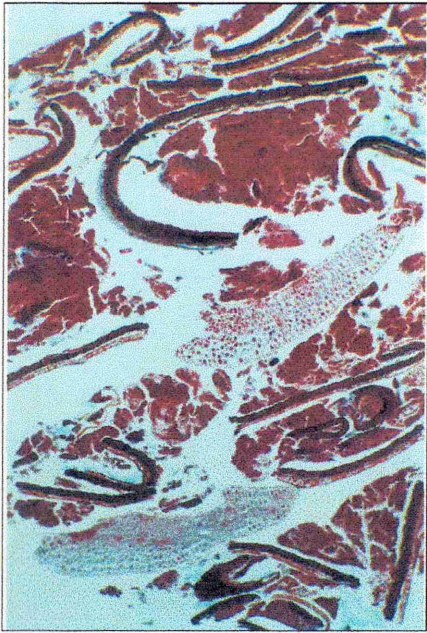


Plate IV Temperature 120 °C



1 mm

contd.



1 mm

Plate V Temperature 150 °C

Figure 6.10 The effect extrusion temperature has on the microstructure of extruded rapeseed. The extruder operating conditions:- screw speed 120rev/min, die size 9 mm, screw compression ratio 3:1 and moisture content 7.5% were constant for the five pictured samples.

6.6.2.4 Milling defect

One sample from each of the preparation treatments assessed in the experiment were sent to BAL for an independent analysis of the milling defect.

A graph showing the results from the analysis of the milling defect of the five extrusion preparation treatments is shown in Figure 6.11. It can be seen in the Figure that, as with the smaller scale experiments discussed in Chapter 5, the greatest milling defect values occur at the high extruder barrel temperatures. As the extruder barrel temperature is reduced the milling defect is also reduced until a critical temperature, below 40°C, is reached and the milling defect value rises.

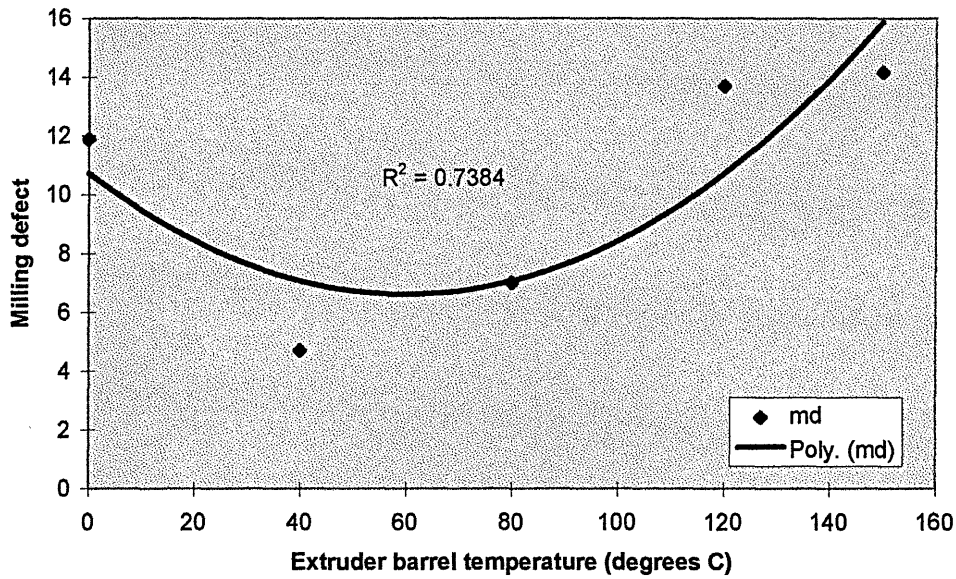


Figure 6.11 *The effect extrusion temperature has on the milling defect.*

A chart comparing the results from the analysis of the milling defect of all of the preparation treatments assessed in this experiment is shown in Figure 6.12. The lowest milling defect value of all of the preparation treatments assessed is extrusion with an extruder barrel temperature at 40°C. The milling defect value for this treatment is 4.71. Extrusion with a barrel temperature at 80°C, conventional preparation of a combined milling and cooking, and the milled treatments all have similar milling defect values of 7, 7.31 and 7.46 respectively. The highest milling defect values were calculated at extrusion temperatures 0°C, 120°C, and 150°C and were 11.89, 13.68 and 14.16 respectively.

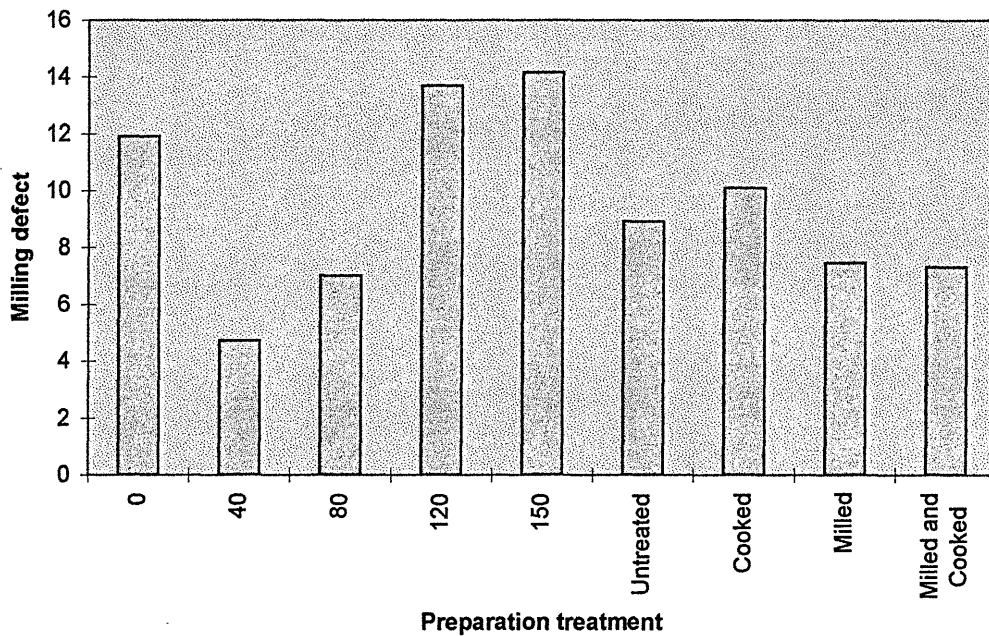


Figure 6.12 *The effect the preparation treatments have on milling defect. * Numerals on preparation treatment axis represents extruder barrel temperature (°C)*

6.7 Experiment 2. The effectiveness of extruding pressed rapeseed as a secondary preparation treatment for second pressing

Experiment 2 is designed to assess the effect extruding pressed rapeseed has on the performance of the screw press at second pressing the rape seed. The experiment will also assess if the extrusion temperature effects the performance of the second press.

6.7.1 Experiment variables

Five extrusion treatments were assessed in the experiment. Untreated rapeseed was first pressed with a Mini 100 screw press, the pressed rapeseed was then extruded at each of the five operating conditions. The extruded samples were then second pressed with the Mini 100 screw press. The residual oil, milling defect and microstructures were recorded and analysed for each trial. The extruder operating variables and rapeseed moisture content chosen for the experiment are detailed in Table 6.2

Table 6.2 *Process variables experiment 2. The effectiveness of extruding pressed rapeseed as a secondary preparation treatment for second pressing*

Rapeseed Moisture Content (db) (%)	Barrel Temperature (°C)	Screw Speed (rev/min)	Die SizeØ (mm)	Screw Compression Ratio	Total Number of Process Conditions
7.5	0 40 80 120 150	120	9	3:1	
1	5	1	1	1	5

Restrictions in equipment availability prevented the trials being replicated.

6.7.2 Analysis of results

An analysis of the residual oil following each stage of the extraction process was carried out for each of the preparation treatments assessed in the experiment. An examination of the seed microstructure and a milling defect analysis was also carried out on each of the preparation treatments.

6.7.2.1 Residual oil analysis

An analysis of the residual oil content in the cake was carried out following the first press, extrusion and the second press.

Figure 6.13 shows the % OIC following pressing of the untreated seed as a preparation for the extrusion process. The x-axis of the chart in Figure 6.13 represents the subsequent extrusion treatment for which the pressed seed was used.

Each of the rapeseed samples represented in Figure 6.13 have undergone the same pressing process and therefore should contain the same residual oil. The chart does however reveal that the pressed rapeseed used for the extrusion treatment with an extruder barrel temperature at 40°C does have a considerably higher % OIC, at 18.9%, than the pressed seed used for the other treatments, all of which are between 15.4 and 16%.

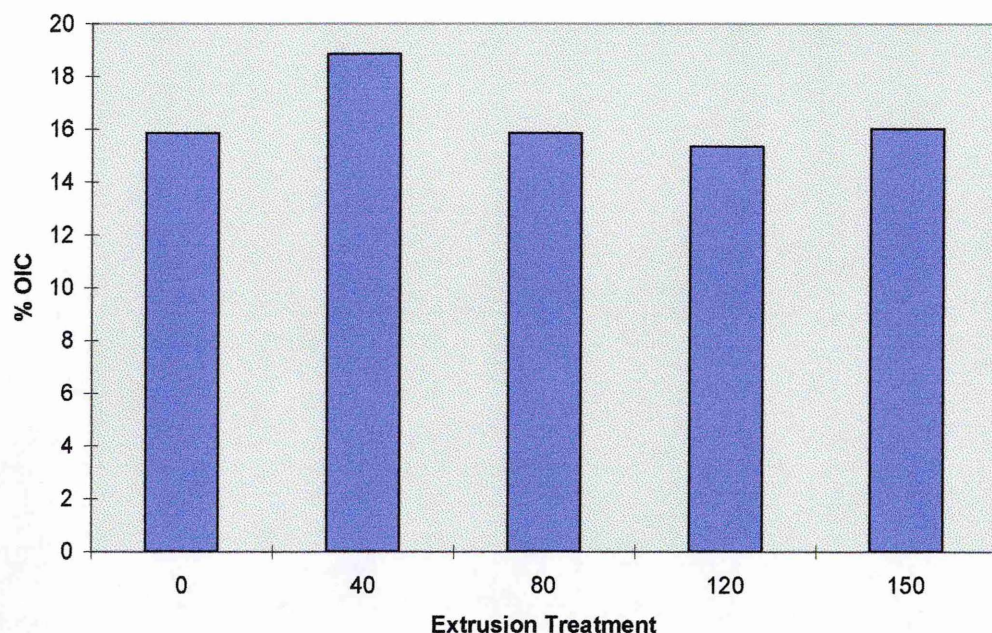


Figure 6.13 *The % OIC following a single pressing of untreated rapeseed prior to extruding. Note: The numerals on the x-axis represent the extruder barrel temperature °C for the subsequent extrusion of the pressed rapeseed.*

A graph showing the percentage residual oil following a single press and extrusion at each of the five processing temperatures assessed is shown in Figure 6.14.

The shape of the graph in Figure 6.14 is virtually identical to the chart in Figure 6.13. The % OIC of the extruded samples are within 0.5% of each other with the exception of the extrusion temperature at 40°C which, as after the initial pressing, is considerably higher.

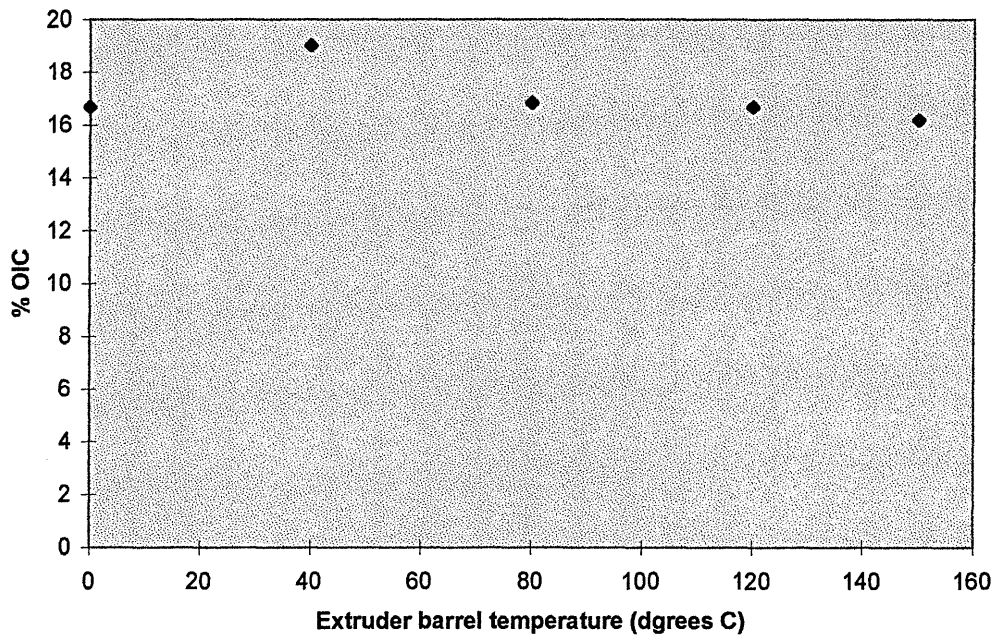


Figure 6.14 *The % OIC of rapeseed following a single press and extrusion*

A graph showing the percentage residual oil in cake following a single press, extrusion at each of the five processing temperatures assessed and a second press is shown in Figure 6.15. The graph shows that the highest % OIC following the second press occurs after extrusion at an extruder barrel temperature of 150°C. The difference between the % OIC following extrusion at extruder barrel temperatures 0, 40, 80 and 120°C is less than 1.5% at 12.7, 13.4, 12.7 and 12.0% respectively.

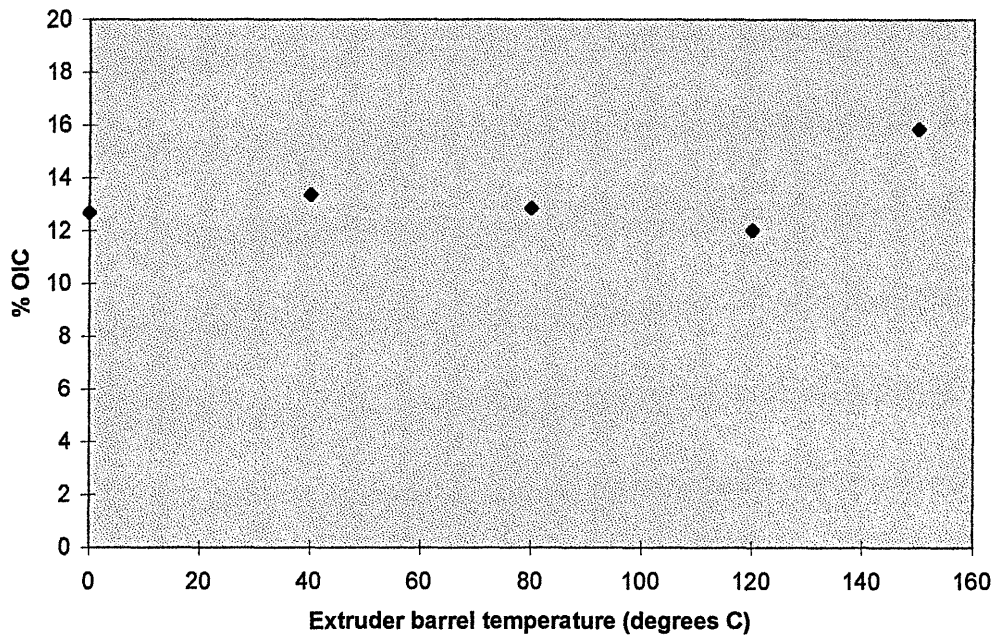


Figure 6.15 *The % OIC following a single press, extrusion and a second press*

6.7.2.2 Extruder throughput

The throughput of the Almex extruder, at each of the five extruder process conditions used in the experiment, was calculated to see what effect the extrusion temperature has on the throughput of the machine.

A sample of the extruded rapeseed, from each of the process conditions, was collected from the extruder over a recorded period of time and weighed. Following an analysis of moisture content and the residual oil of the single pressed and extruded rapeseed, the machine throughput for each process condition could be calculated. The throughput of the Almex extruder at each of the extrusion temperatures assessed can be seen in Figure 6.16.

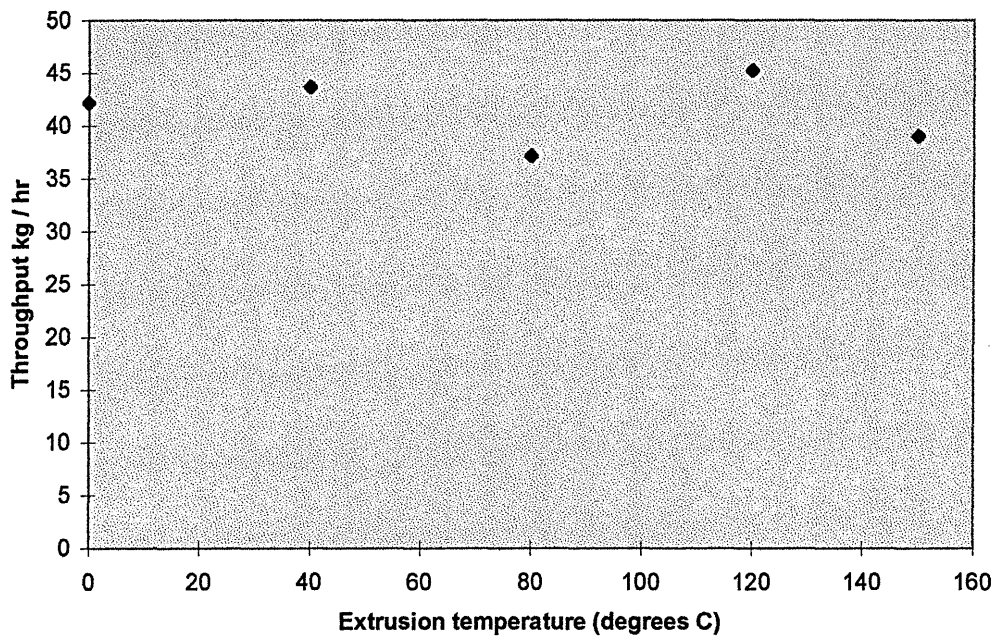


Figure 6.16 *The effect extrusion temperature has on the throughput of the Almex extruder extruding single pressed rapeseed*

The results of the throughput analysis reveal that the throughput is relatively consistent over the full range of temperatures assessed. The lowest throughput of 37.16 kg/hr was identified at an extrusion temperature of 80°C and the highest of 45.28 kg/hr at 120°C. No statistical relationship between extrusion temperature and machine throughput was identified in the analysis of results of the experiment.

6.7.2.3 Microscopy

A number of samples from the single pressed untreated rapeseed, pressed in preparation for extrusion, were prepared and mounted for an analysis of the microstructure with a light microscope. The microscopy was carried out to assess to what extent the seed cell structure is damaged during screw pressing. The image of the seeds microstructure, following screw pressing, will also enable an assessment of to what extent, if any, the subsequent extrusion of the pressed rapeseed increases its cell damage in preparation for a second press.

The microstructures of two screw pressed samples are shown in Figure 6.17. The sample represented in Plate I and that in plate II were subsequently extruded at 0°C and 80°C respectively. As all of the pressed samples used in the experiment underwent exactly the same processing and the microstructures of the 5 screw pressed samples were so similar, it was not deemed necessary to picture all five samples. The only difference between the two pictured samples is the orientation of the sample.

Plates I and II both reveal a relatively high percentage of damage to the microstructure of the rape seed, however there is still evidence of clusters of undamaged cells depicted with by the letter A. The clusters of undamaged cells indicates that there is scope for an improvement in the preparation for a second press with a further treatment process that would break open the remaining undamaged oil cells increasing the availability of oil.

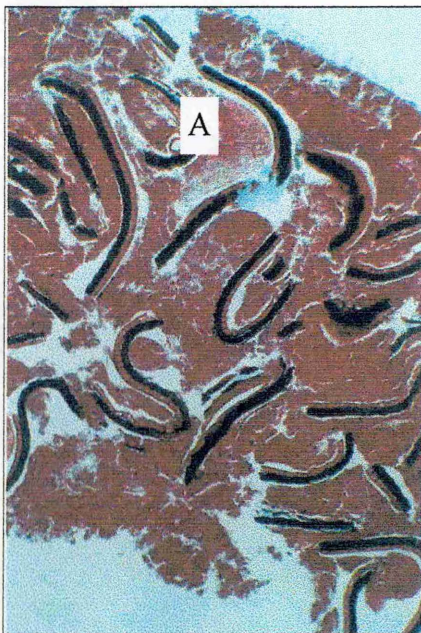


Plate I

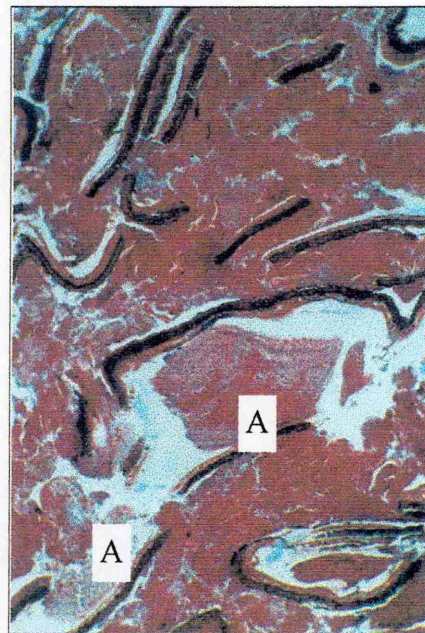


Plate II

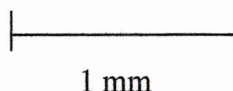


Figure 6.17 The microstructure of cold whole rapeseed single pressed in preparation for extrusion.

An analysis of the rapeseed microstructure from each of the process conditions was carried out to assess what effect a wide range of extrusion temperatures has on the microstructure of pre-pressed rape seed extruded with the Almex extruder.

The microstructures of the five samples extruded at 0, 40, 80, 120 and 150°C are shown in Figure 6.18. The microstructures of the five pressed and extruded rapeseed samples pictured in Plates I to V reveal extensive cell damage with little, or no, sign of any cell structure in any of the five samples. The few remaining clusters of undamaged cell structure that were identified, following the pressing of the untreated rapeseed, have been completely eradicated using extrusion as secondary stage preparation treatment.



Plate I Temperature 0 °C

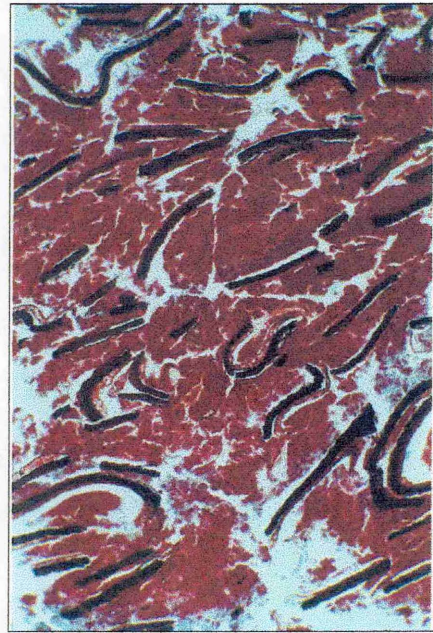


Plate II Temperature 40 °C

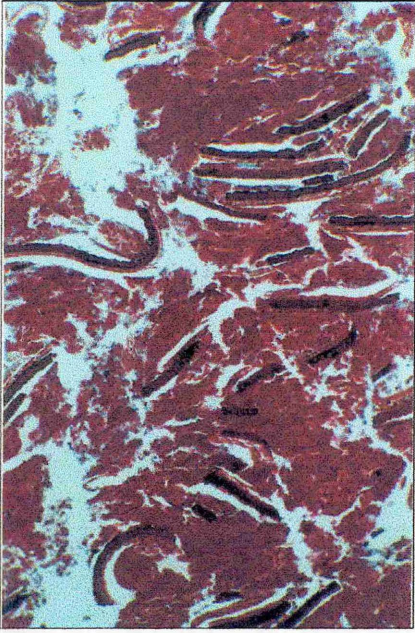


Plate III Temperature 80 °C



Plate IV Temperature 120 °C



Plate V Temperature 150 °C

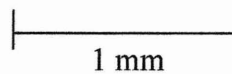


Figure 6.18 The effect extrusion temperature has on the microstructure of single pressed and extruded rapeseed. The extruder operating conditions:- screw speed 120 rev/min, die size 9 mm, screw compression ratio 3:1 and moisture content 7.5% were constant for the five pictured samples

6.7.2.4 Milling defect

A sample from each pressing and extrusion preparation treatments assessed in the experiment were sent to BAL for an independent analysis of the milling defect.

Figure 6.19 shows the milling defect following pressing of the untreated seed as a preparation for the extrusion process. The x-axis of the chart in Figure 6.19 represents the subsequent extrusion treatment for which the pressed seed was used.

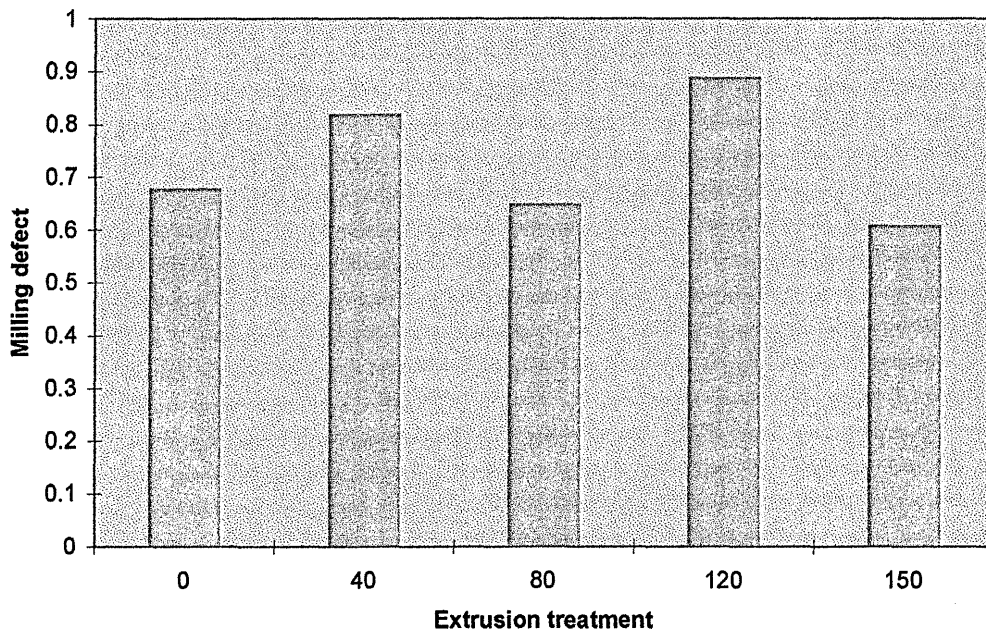


Figure 6.19 The milling defect following a single pressing of untreated rapeseed prior to extruding. Note: The numerals on the x-axis represent the extruder barrel temperature °C for the subsequent extrusion of the pressed rapeseed

Each of the rapeseed samples represented in Figure 6.19 have undergone the same pressing process and therefore should have the same milling defect value. The chart reveals that, although there is some deviation in the milling defect results, the difference in milling defect values for the pressed rapeseed are very small with all the values between 0.61 and 0.89. The mean milling defect value following a single pressing of untreated seed is 0.73.

A graph showing the results from the analysis of the milling defect following a single press and extrusion at each of the five processing temperatures assessed is shown in Figure 6.20. As with the results from the analysis of the milling prior to extrusion shown in Figure 6.19, the difference in the milling defect values between the different extrusion treatments are very small with values ranging between 0.25 and 0.4. The mean milling defect value following a single pressing and extrusion at each of the five processing temperatures 0.35.

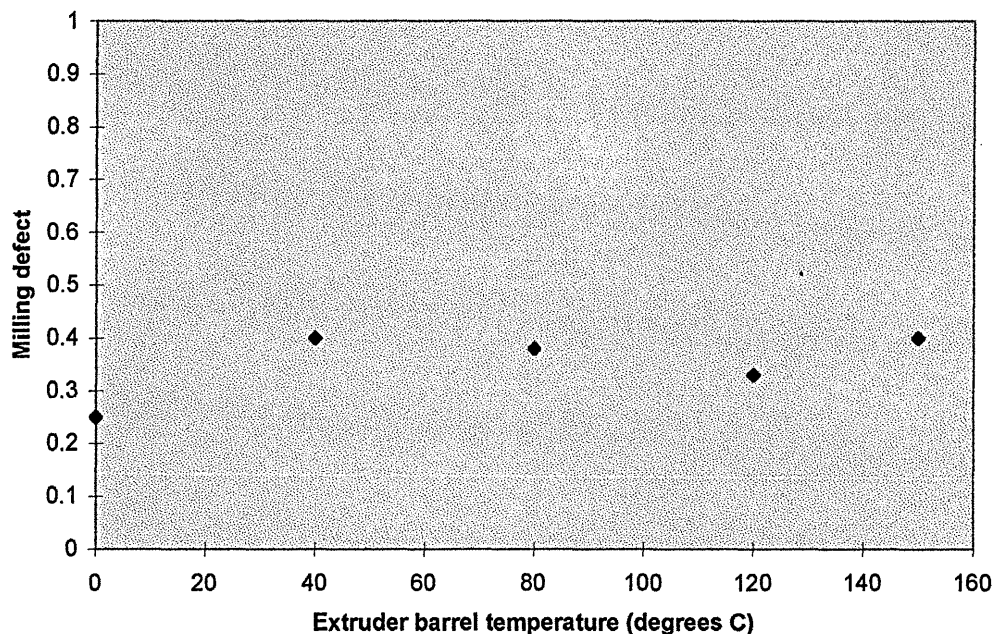


Figure 6.20 *The milling defect following a single pressing and extrusion*

6.8 Discussion

The large scale extrusion experiments provided an indication on the effectiveness of extrusion as a preparation process, compared to more conventional preparation treatments, for the mechanical extraction of oil. The experiments also identified the significance of extrusion temperature as a process variable for a larger scaled process than previously assessed in the research, and how the effectiveness of the larger scale extrusion process as a preparation treatment for rapeseed compares to the smaller laboratory scaled extrusion. The findings from the experiments are discussed in the following section.

6.8.1 Extrusion of untreated rapeseed

As with the laboratory scaled Brabender extrusion experiments, the extrusion temperature, when extruding with the Almex extruder, proved to be a significant factor in the preparation of untreated rapeseed.

An analysis of the residual oil, following extrusion at a range of temperatures, identified that the amount of oil released from the rapeseed during extrusion increased as the extrusion temperature was decreased until a critical temperature below 40°C was reached, at which point, the amount of oil released reduced dramatically. A factor why there is no oil released during extrusion at the extreme low temperatures assessed is that the rapeseed oil will be more viscous at the low temperatures restricting it flowing from the seed.

The analysis of the microstructures of the extruded rapeseed, at the different extrusion temperatures, supports the results from the residual oil in cake analysis showing the degree of seed cell structure damage increasing with a reduction in extrusion temperature again until a critical extrusion temperature, below 40 °C, when the degree of cell damage is minimal.

A possible reason for an increase in damage to the seed cell structure as the processing temperature is reduced is at lower temperatures the seed will become more brittle making the cracking of the seed much easier. At elevated temperatures the seed will become more pliable and susceptible to deformation during extrusion. The ability of the seed to deform without breaking will make the grinding process during extrusion less effective resulting in a greater percentage of non-ruptured oil cells. It is considered that the reason for a reduction in cell damage during extrusion at 0°C is that the frictional properties at such low temperatures make grinding the seed difficult. The seed becomes free flowing and much of the seed passes through the extruder undamaged.

The analysis of the milling defect following extrusion of untreated rapeseed at the range of processing temperatures assessed in the experiment followed the same pattern as identified with the analysis of residual oil and the analysis of microstructure following extrusion. The milling defect values decreased with a reduction in processing temperature until a critical point, again below 40°C, was reached and the milling defect value increased rapidly. The lowest milling defect value recorded from the five extrusion temperatures assessed was achieved following extrusion at 40°C with a value of 4.71. Extruding untreated rape seed at 40°C was the only processing temperature assessed in the experiment that gave a milling defect value that was within the commercially accepted limits for the preparation of rapeseed for the mechanical extraction of oil.

The throughput of the Almex extruder, when extruding untreated rapeseed, unlike the Brabender extruder, was effected by the extrusion temperature. At a processing temperature of 0°C the throughput was over 50 kg/hr, at 150°C the throughput was as low as 8.80 kg/hr and at processing temperatures 40°C, 80°C and 120°C the throughputs were 26.55, 20.07 and 23.63 kg/hr respectively.

The differences in the throughput of the extruder was visually evident during the experimentation. At the extrusion temperatures 40°C, 80°C and to some extent at 120°C the release of oil during the extrusion process did tend to reduce the throughput of the machine. The initial difficulties encountered with oil saturation described in the beginning of this chapter were alleviated with the introduction of an oil drain and a positive feed system, the excess free oil in the extrusion barrel did however still inhibit the throughput of the extruder.

At an extrusion temperature of 0°C there was no problem with excess free oil in the extruder barrel, the analysis of the residual oil following extrusion revealed that virtually no oil was released during the extrusion process and the throughput of the extruder was considerably greater.

The lowest extruder throughput was calculated at an extrusion temperature of 150°C even though, as with the extrusion at 0°C, there was very little oil released during the extrusion process. It was however observed during extrusion at this elevated temperature that the throughput of the machine was very inconsistent. The high temperatures appeared to bake the rapeseed at the extruder die restricting the flow of the extruded material until a high pressure build up behind the die forced the blockage. The high build up of pressure caused the extruded rapeseed to violently discharge from the die spraying the hot extruded seed as far as approximately 3 metres from the machine.

6.8.2 Pressing extruded rapeseed

The analysis of the residual oil in the press cake following a single pressing of the extruded rapeseed followed a similar pattern as was identified with the analysis of the microstructures of the extruded rapeseed prior to the pressing. The residual oil in press cake was lower with each incremental drop in processing temperature between 120°C and 40°C and a large increase in the residual oil in the press cake was apparent below a processing temperature of 40°C. The residual oil following extrusion at 150°C was however lower than would have been expected compared to that following extrusion at 40, 80 and 120°C.

The most probable reason for the discrepancies between the residual oil analysis following a single press and the analysis of the microstructures of the extruded rapeseed, is the larger than desirable spread in the residual oil in press cake between the replications at both 80 and 120°C. The spread in the residual oil results at 80°C was 2.83% ranging from 12.86% OIC to as high as 15.69% OIC, the spread at 120°C was 2.5% ranging from 13.86% OIC and 16.36% OIC between the three replications.

It is thought that the reason for the large spread in results at 80°C and 120°C is related to the throughput of the extruder. It has previously been discussed that the throughput of the Almex extruder, when extruding untreated rapeseed, varied considerably with different extrusion temperatures and that the throughput for all of the operating temperatures assessed, with the exception of an extrusion temperature of 0°C, was far below the 50 kg/hr throughput of the mini 100 screw press.

The unmatched throughput of the two machines resulted in inconsistent feeding of the press, with the press often being starve fed (pressing below the press capacity). DeSmet Rosedowns Ltd., the screw press manufacturers, established that starve feeding of the press is likely to cause inconsistent press performance, which would account for the large spread in results.

The analysis of the residual oil in the press cake, following a double pressing of the extruded rapeseed, again followed a similar pattern as was identified with the analysis of the microstructures of the extruded rapeseed prior to the pressing and with the residual oil analysis following a single press, with the exception of the analysis of results following extrusion at a process temperature of 0°C. The mean residual oil in press cake increased by 0.83 % between extrusion temperatures 150°C and 120°C. The residual oil then reduced with each incremental drop in processing temperature between 120°C and 0°C.

The spread of the results of the residual oil analysis, between replications of each of the operating temperatures assessed, were much less than the results following a single press with a maximum spread of 1% at extrusion temperature 150°C. The feeding of the press for the second pressing was much more consistent than for the first press as the process did not depend on the throughput of the Almex extruder. The first pressing of the whole sample was completed before the second press started, this enabled the press to be flood fed ensuring that the press operated at its full capacity. The consistency of the pressing procedure resulted in a high degree of repeatability for each replication.

The consistency of the results following the second press, with the press being flood fed, supports the assumption that the inconsistency of the results following a single press was due to the pressing procedure rather than the extrusion process.

6.8.3 Non-extrusion preparation treatments

The analysis of the residual oil in the press cake following a single pressing of untreated rapeseed, cooked seed, milled seed and a combination of first milled and then cooked seed, the latter of which is to represent a conventional preparation treatment, identified

the combination of milling and cooking proved to be significantly more effective than the other non-extrusion preparation treatments.

The combination of milling and cooking did however prove difficult to both single and double press. The finely milled rapeseed at a moisture content of approximately 5% produced a high percentage of foots in the oil. The quantity of foots produced during the second pressing stage was so excessive that a residual oil analysis following the second press was not possible.

The analysis of the residual oil following both a single press and a double press revealed that there was no significant benefit to be gained from either cooking or milling rape seed as an individual preparation treatment for pressing.

The analysis of the milling defect for the non-extrusion preparation treatments reveal that there is little difference between a combination of both milling and cooking as a preparation treatment, or just milling without the cooking stage of the process. This would indicate that the cooking stage of the preparation treatment does not affect the effectiveness of the preparation treatment.

6.8.4 Comparison between extrusion and non-extrusion treatments

The analysis of residual oil following a single press would imply that extrusion, at all of the process temperatures assessed with the exception of extrusion at an operating temperature of 120°C, is as an effective preparation treatment for the mechanical extraction of oil as the conventional two stage preparation treatment of milling and cooking. The analysis does not however suggest that the extrusion process is more effective than conventional preparation treatments at making available oil for mechanical extraction with a screw press.

The analysis of the milling defect of both extruded and non-extruded preparation treatments contradicts the above paragraph. The analysis suggest that using extrusion, at an operating temperature of 40°C, is more effective, as a preparation of rapeseed for the mechanical extraction of oil, than the conventional two stage preparation treatment of milling and cooking.

6.8.5 Pressing untreated rapeseed

A sample of untreated rapeseed was pressed, prior to extrusion, for each of the five extruder operating conditions assessed in experiment 2. An analysis of the microstructures of each of the pressed samples revealed that although the pressing process damaged a majority of the seed cell structure, clusters of undamaged cells still were evident.

An analysis of the milling defect of the untreated rapeseed following a single press revealed that the pressing process produced a product with a low milling defect value with a mean value of 0.73 for the five samples analysed. The milling defect values from the five analysed samples showed little variation all of which with milling defect values ranging from 0.61 and 0.89. A high level of consistency in the milling defect values would be expected as the five samples underwent the exact same pressing procedure.

6.8.6 Extruding pressed rapeseed

The analysis of the microstructures following a single press and extrusion, at all five of the extruder operating temperatures assessed, revealed that the process had successfully ruptured any undamaged oil cells remaining from the screw pressing. The extrusion temperature did not appear to make any difference to the microstructure of the rapeseed following a single pressing and extrusion.

The results of the throughput analysis of the Almex extruder, when extruding pre-pressed rapeseed, reveal a much greater consistency in throughput throughout the full range of temperatures assessed than was identified when extruding untreated seed. The throughput of the extruder extruding single pressed rapeseed is greater, than when extruding untreated rapeseed, at all of the extrusion temperatures assessed with the exception of extruding at 0°C. The mean increase in extruder throughput when extruding pressed rapeseed, as opposed to untreated rapeseed, over the full range of extrusion temperatures was over 15 kg/hr matching the throughput of the extruder much closer to that of the screw press used for the experiment.

The likely reason for the increase in extruder throughput when extruding single pressed rapeseed is the absence of free oil in the extruder barrel during extrusion. With the rapeseed having previously been pressed, the majority of the free flowing available oil would have been expelled, and, due to the much lower oil content of the pressed rapeseed, any oil that is released from the rapeseed as a result of the extrusion process, would be rapidly reabsorbed in the meal. It has already been established that the extruder throughput of the extruder is inhibited when there is an excess of free oil in the extruder barrel.

The analysis of the rapeseed milling defect following a single pressing and extrusion, at the range of processing temperatures assessed in the experiment, supported the analysis of microstructure previously discussed in this section, which revealed that the extrusion process, at all of the extruder operating temperatures assessed, successfully ruptured the small percentage of undamaged cells remaining in the cake following a single press.

The milling defect values following extrusion were consistently lower than milling defect following pressing at all five of the extrusion temperatures assessed in the experiment. The mean milling defect values following pressing and extrusion at the five process temperatures assessed was 0.35. The difference in the milling defect values between the five processing temperatures was negligible ranging from 0.25 and 0.4, which again would indicate that the extruder processing temperature does not affect the performance of the extruder when processing pre-pressed rapeseed.

6.8.7 Second pressing pressed and extruded rapeseed

The analysis of the residual oil in the press cake following a single pressing, extrusion at the five extrusion temperatures assessed in the experiment, and a second pressing again revealed little difference between the samples extruded at different temperatures with the exception of the pressed sample following extrusion at 150°C. The difference in the residual oil content of the pressed cake following extrusion at 0, 40, 80, and 120°C was less than 1.5% ranging between 12.0 and 13.4%. The residual oil of the press cake following extrusion at 150°C was significantly higher than the residual oil content following extrusion at lower extrusion temperatures with an oil content of 15.9%. With the absence of any replication of the trials in this experiment, the unexpected high residual oil in the press cake identified following extrusion at 150°C could possibly be due to error and not as a result of the process condition.

The mean difference in residual oil content of the press cake between the first press and the second press, when using extrusion as an intermediate preparation prior to the second press, was 3.03%. In experiment 1, the analysis of the residual oil content of the non-extrusion preparation treatments identified that when double pressing untreated rapeseed, the difference in the residual oil content of the press cake between the first and second press was 2.74%.

A comparison between residual oil analysis of the two experiments reveal that the mean residual oil in the press cake following a single pressing of untreated rapeseed is 1% higher in experiment 2 than in experiment 1. The comparison of the analysis also reveals that following a second press, experiment 1 directly following the first press and in experiment 2 following an intermediary preparation treatment, the mean residual oil content is 0.72% higher in experiment 2. Two unexpectedly high figures in the results of the residual oil analysis in experiment 2, the first following a single press of untreated rapeseed prior to the subsequent extrusion at an extrusion operating temperature of 40°C, and the second, following a second press of the rapeseed extruded at 150°C, does account for the higher mean residual oil contents identified in experiment 2.

The comparison between the oil analysis would suggest that there is no significant advantage to be gained by extruding pressed rapeseed as an intermediary preparation treatment prior to a second press.

6.9 Conclusion

1. The analysis of extruded rapeseed microstructure, milling defect and residual oil following pressing all identified that extrusion processing temperature is a significant factor in the effectiveness of the extrusion process in the preparation of rapeseed.
2. Analysis of the microstructure of extruded rapeseed revealed that the greatest damage to the cell structure occurred following extrusion at a barrel temperature of 40°C.
3. Analysis of the milling defect of extruded rapeseed revealed that the lowest milling defect value was calculated following extrusion at a barrel temperature of 40°C. The milling defect value of 4.71 is within the expected range for commercial preparation.

4. The milling defect of rapeseed extruded at a barrel temperature of 40°C was lower than that of the simulated traditional preparation treatment of flaking and conditioning.
5. Analysis of the residual oil in the press cake following both extrusion and a single press, and simulated traditional preparation treatments and a single press, revealed that there was no significant difference in oil yield between extrusion at barrel temperatures 0, 40, 80 and 150°C, and the traditional rapeseed preparation treatment of combined flaking and conditioning.
6. Analysis of the residual oil in the press cake following both extrusion and a double press, and simulated traditional preparation treatments and a double press revealed the greatest oil yield occurred following extrusion at barrel temperatures of 0 and 40°C. There was no significant difference in the residual oil in the press cake following a double press between extruder barrel temperatures 0 and 40°C.
7. No significant improvement in oil yield is achieved from using extrusion as a secondary preparation treatment of pressed rapeseed subsequent to a second press.

7. COMMERCIAL VIABILITY ASSESSMENT OF EXTRUSION AS A PREPARATION TREATMENT

7.1 Introduction

The initial section of this chapter investigates the economics of current oilseed processing practices comparing the investment and operating costs associated with commercial scaled solvent and mechanical extraction plants. The cost attributed to the preparation of rapeseed and what effect a reduction in preparation costs will have on the overall profitability of the mechanical oil extraction process is identified and discussed.

The second section of the chapter investigates the economics of introducing high pressure single screw extrusion to a mechanical extraction process as an alternative preparation treatment to those currently employed in the oil extraction industry.

The final section of the chapter compares and discusses the commercial viability of the investigated processing scenarios for the introduction of high pressure single screw extrusion with traditional commercial solvent and mechanical extraction processes.

7.2 Rapeseed oil extraction plant investment and processing economics

The economics of two hypothetical 1000 metric tonnes per day (MTPD) rapeseed oil extraction plants are analysed and discussed comparing investment costs, operating costs and potential profit margins from the two processes.

The first processing plant analysed is a full press mechanical extraction plant. The preparation treatments used in the plant consist of flaking and conditioning. The preparation is followed by a low pressure screw pre-press and finally a high pressure second screw press.

The second process analysed is a pre-press / solvent extraction plant. As with the mechanical extraction plant, the preparation treatments used in the plant consists of flaking and conditioning is followed by a low pressure screw pre-press. Following the pre-press the residual oil in the rapeseed press cake is extracted by a final solvent extraction process.

The information concerning the economics of the processing plants was obtained from commercial sources within the European oil processing industry and published literature. Due to the commercially sensitive nature of some of the information obtained within the chapter it has been requested from both equipment manufacturers and suppliers, and oil processors that the sources of certain information remain anonymous.

7.2.1 Investment costs

An estimation of the overall investment costs, together with a breakdown of the individual equipment costs, not including installation, has been determined for each of the processing procedures examined. The investment costs for both mechanical and solvent extraction processing plants are shown in Table 7.1.

Table 7.1 *The comparison of the overall investment requirement and a breakdown of the equipment costs between a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

	Mechanical Extraction	Solvent Extraction
Total investment cost (£)¹	6,600,000	10,000,000
Equipment cost (£)²		
Flaking roll	400,000	400,000
Conditioner	1,060,000	1,060,000
Press ³		
pre-presses	500,000	500,000
second press	2,000,000	
Solvent plant		2,500,000
Conveyors and pumps etc. ⁴	594,000	669,000
Total Equipment Cost (£)	4,554,000	5,129,000

¹ The total investment cost includes the equipment, installation and the cost of buildings.

² The equipment cost does not include installation.

³ A manufacturer of screw presses stated that a press specification capacity of 500 MTPD is quoted as a pre-press capacity. The capacity of the press being used for a second high pressure press is reduced to approximately 100 - 125 MTPD, therefore, four second presses are required to match the throughput of each pre-press. The investment cost required for the presses has therefore been based on the purchase of 10x500 MTPD screw presses. The solvent extraction plant does not require a second press.

⁴ An equipment manufacturer suggested that a guide for the calculation of the investment requirement for the materials handling equipment (conveyors and pumps) is 15% of the total equipment investment, this figure has therefore been used in the calculation of investment for both the mechanical and the solvent extraction processes.

7.2.2 Processing economics

The economics of rapeseed oil extraction has been investigated and a comparison of production efficiency and operating costs, along with potential profits, of both mechanical and solvent oil extraction plants has been presented.

7.2.2.1 Gross profit

The revenue and gross profit of both the mechanical and solvent oil extraction processes investigated in the study when processing rapeseed was calculated and is shown in Table 7.2. The oil content of rapeseed is between 40 and 46% depending on variety and growing conditions. For this exercise the oil content of the raw rapeseed was assumed to be 43%.

Table 7.2 *The comparison of the calculated revenue and gross profit per tonne of processed rapeseed for a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

	Mechanical Extraction	Solvent Extraction
Extraction efficiency		
Seed (kg)	1000	1000
Yield (%) ¹	85.5	98.5
Oil extracted (kg)	367.65	423.5
Meal (kg)	632.35	576.5
OIC (%)	9.9	1.1
Product cost		
Seed cost (£/t) ²	125	125
Oil price (£/t) ²	263	263
Meal price (£/t) ³	71.25	64.78
Revenue		
Oil (£ per t of seed)	96.69	111.39
Meal (£ per t of seed)	45.05	37.34
Total	141.74	148.73
Seed (£/t)	125.0	125.0
Gross profit (£/t)	16.75	23.74

¹ An oil yield of 85.5% for the mechanical oil extraction plant was calculated from information obtained from a UK vegetable oil processor that operates a full press oil extraction plant for rapeseed. The solvent extraction oil yield was calculated to give a % OIC of approximately 1%, a figure that is considered as typical for modern commercial solvent extraction plants.

² The seed cost and crude oil price was provided by a UK oil processor and was current as of the 26th October 1999.

³ Meal price was calculated as the average price from two separate UK sources. A UK vegetable oil processor that operates a full press oil extraction plant for rapeseed quoted a meal price of £60 per tonne which includes a bonus of approximately 10% for high OIC (10%). A large UK animal feed mill quoted a meal price of £75 per tonne for solvent extracted meal at 1% OIC. The mill predominantly uses solvent extracted meal, however they did confirm that they would negotiate a premium price with a supplier for a high oil content meal should the case arise.

A comparison in the gross profit per tonne of processed rapeseed, calculated for both the 1000 MTPD mechanical and solvent oil extraction process, revealed that the gross profit is approximately £7 per tonne of processed seed greater with the solvent extraction plant than with a mechanical extraction plant.

7.2.2.2 *Operating cost*

The major operating costs for the two processing plants have been investigated to enable the net operating profit of the two plants to be calculated. Table 7.3 shows the comparison of the calculated operating cost and net profit per tonne of processed rapeseed.

Table 7.3 *The comparison of the calculated operating cost and net profit per tonne of processed rapeseed for a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

	Mechanical Extraction		Solvent Extraction	
Consumable				
<i>Electricity</i> ¹		<i>(kWh per tonne of seed)</i>		<i>(kWh per tonne of seed)</i>
Flaking		8		8
Conditioning		2		2
Pressing		55		15
Solvent plant		-		5
Conveyors and pumps		10		10
etc.				
<i>Total (kWh/t)</i>		75		40
Steam (t per t of seed at 11 bar) ²		0.175		0.300
Hexane (l. per tonne of seed) ²		-		1
Variable cost				
		<i>(£/t)</i>		<i>(£/t)</i>
Electricity (£/kWh) ³	0.0336	2.52	0.0436	1.74
Steam (£/t) ⁴	17.5	3.06	17.5	5.25
Hexane (£/l.) ⁵	-	-	0.185	0.185
<i>Total Variable Cost</i>		5.58		7.18
Semi variable cost				
Maintenance ⁶		3.5		3.5
Personnel ²	20		28	
Salary per annum £ ⁷	20,000	1.3		1.9
Gross profit (£/t)		16.75		23.74
Operating cost (£/t)		10.42		12.55
Net profit (£/t)		6.33		11.19

¹ The breakdown of the electrical energy requirement for each stage of the oil preparation, oil extraction and materials handling for the two oil extraction processes examined were calculated from information provided by a large European oil processing equipment manufacturer and supplier, and from a published paper by Stroup (1997).

² The steam and hexane use together with the personnel requirement for both mechanical and solvent extraction processes were provided by a large European oil processing equipment manufacturer and supplier.

³ The cost of electricity is based on information of electricity charges quoted in a telephone conversation with a representative of Eastern Electricity plc business tariffs. The unit cost quoted in Table 7.3 incorporates the average unit tariff, monthly charges, including meter and standing charges, and a yearly maintenance charge. The difference in cost per unit between the mechanical and the solvent extraction plants is due to the higher yearly demand for electricity for the mechanical plant allowing a lower average unit tariff.

⁴ The energy cost to produce steam for seed conditioning and during the solvent extraction process was calculated based on information within a published paper by Marchand (1986). The paper quoted the cost to produce a tonne of steam using gas fuel was approximately 110 Ffr. An implied GDP Deflator at Market Prices, HMSO (1997) was used to calculate the 1997 cost to produce a tonne of steam that is equivalent to 110 Ffr in 1986 stated by Marchand (1986). A conversion rate of 10.2 Ffr. = £1 was used to convert the energy cost to £ sterling.

⁵ The current cost of hexane was provided by a UK vegetable oil processor who operates a solvent extraction processing plant.

⁶ No specific information on maintenance cost was available for a mechanical oil extraction process or a solvent extraction plant processing rapeseed, however an analysis of the operating cost of a solvent extraction soybean plant was carried out by a large European oil processing equipment manufacturer and supplier. The maintenance cost stated in the analysis of operating cost for the soybean plant was therefore used for the purpose of this study.

⁷ The cost of personnel to operate the extraction plants was not made available from the oilseed processors questioned therefore an annual cost of £ 20,000 per person was assumed for the purpose of the study.

A comparison in the net profit per tonne of processed rapeseed, calculated for both the 1000 MTPD mechanical and solvent oil extraction process, revealed that the net profit is approximately £5 per tonne of processed seed greater with the solvent extraction plant than with a mechanical extraction plant.

7.2.3 Annual profit

The annual profit that can be achieved from processing rapeseed with each of the plants examined has been calculated and the results shown in Table 7.4.

Table 7.4 *The comparison of the calculated annual profit for a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

		Mechanical Extraction	Solvent Extraction
Investment (£)		6,600,000	10,000,000
Capacity MTPD	1000		
Annual days of operation	330		
Yearly capacity	330,000		
Net Profit (£/t)		6.33	11.19
Annual operating profit (£)		2,088,900	3,692,700

The results show that the annual operating profit achievable from the solvent extraction plant is considerably greater than that of the mechanical extraction plant. It should however be noted that the calculation of the annual operating profit shown in Table 7.4 only took into consideration the extraction plant operating costs that could be directly attributed to the extraction process. The calculation does not include costs additional to the extraction process that would be associated with an oil extraction business such as managerial, sales and administration costs or plant and personnel insurance etc.

The calculation of the annual profit for the two extraction plants was also based on the scenario that the plant would be operating at full capacity for 330 days a year. Any disruption to the process, such as downtime for repairs and service of equipment, would result in a decrease plant throughput and reduce the obtainable revenue. The actual profit from the oil extraction process would then be less than the figure identified in Table 7.4.

7.2.4 Pay back period

The payback period on the capital investment of both the mechanical and solvent extraction plants have been calculated and the results shown in Tables 7.5 and 7.6. The calculation has been based on the total investment cost, identified in Table 7.1, and the annual operating profit identified in Table 7.4.

Table 7.5 shows the payback period based on a scenario that the processing company had available funds to pay the required capital investment without securing a bank loan.

Table 7.6 shows the payback period based on the scenario that the processing company did not have the funds available for the investment and therefore required a loan that was charged at an annual interest rate of 10%.

Table 7.5 *The comparison between the pay back period on the initial plant investment for a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

	Year	1	2	3	4
Mechanical Extraction	Op. Balance	-6,600,000	-4,511,100	-2,422,200	-333,300
	Profit	2,088,900	2,088,900	2,088,900	2,088,900
	Cl. balance	-4,511,100	-2,422,200	-333,300	1,755,600
Solvent Extraction	Op. Balance	-10,000,000	-6,307,300	-2,614,600	
	Profit	3,692,700	3,692,700	3,692,700	
	Cl. balance	-6,307,300	-2,614,600	1,078,100	

Table 7.6 *The comparison between the pay back period on the initial plant investment including a 10% annual interest payment for the investment loan for a 1000 MTPD mechanical oil extraction plant and an equivalent capacity solvent oil extraction plant.*

	Year	1	2	3	4
Mechanical Extraction	Op. balance +	-6,600,000	-4,962,210	-3,160,641	-1,178,915
	10% int.				
	Profit	2,088,900	2,088,900	2,088,900	2,088,900
	Cl. balance	-4,511,100	-2,873,310	-1,071,741	909,985
Solvent Extraction	Op. balance +	-10,000,000	-6,938,030	-3,569,863	
	10% int.				
	Profit	3,692,700	3,692,700	3,692,700	
	Cl. balance	-6,307,300	-3,245,330	122,837	

The calculated pay back period on the capital investment of both the mechanical and solvent extraction plants shown in tables 7.5 and 7.6 reveal that, for both scenarios examined, the return on capital investment will occur during the fourth year of operation for the mechanical extraction plant and, during the third year of operation for the solvent extraction plant.

7.3 The effect process efficiency, market prices and operating costs have on the commercial viability of mechanical extraction.

The following section identifies the effect that the efficiency of the mechanical extraction process, the market price of high oil content rapeseed meal and energy requirement of the extraction process has on the commercial viability of the mechanical extraction process compared to the more profitable solvent extraction process.

7.3.1 Extraction efficiency

An investigation was carried out to show how the extraction efficiency of the 1000 MTPD mechanical extraction plant examined in the study effects the profitability of the extraction process. A calculation of the net profitability of the process at a range of extraction efficiencies was carried out using the processing figures identified in Tables 7.2 and 7.3. By changing only the % oil yield figure in Table 7.2 the effect the extraction efficiency has on the profitability of the process could be assessed. The graph in Figure 7.1 identifies the results from the investigation and shows at what extraction efficiency the mechanical extraction process will match the achievable net profit of a solvent extraction plant of the same capacity.

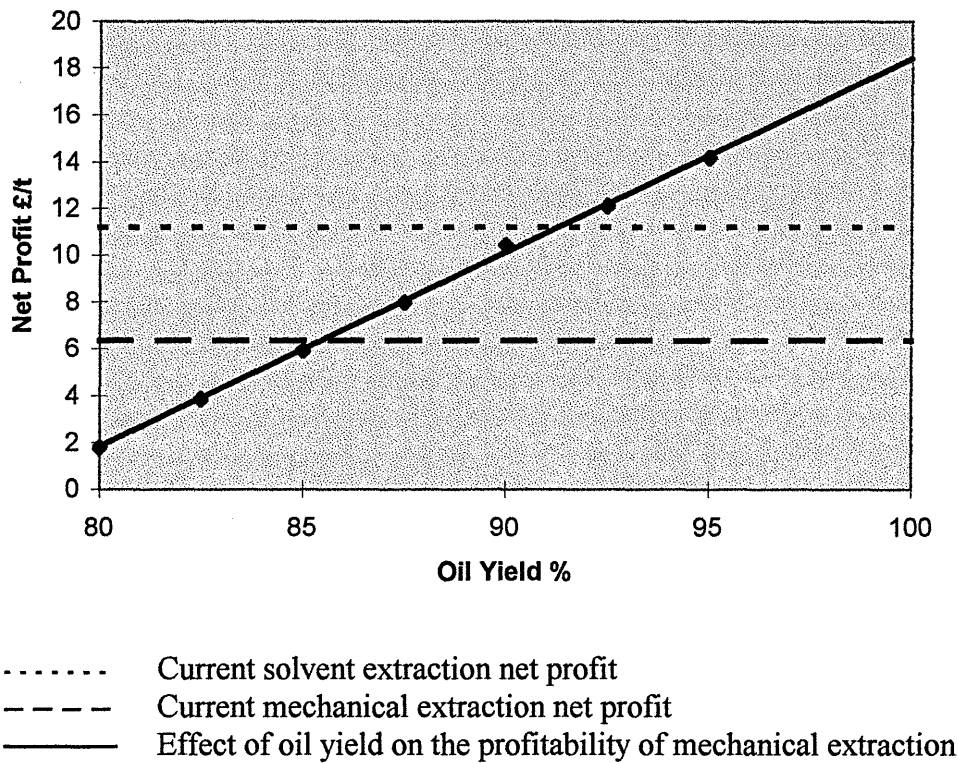


Figure 7.1 The effect the % oil yield of a 1000 MTPD mechanical extraction plant has on the profitability of the process compared to a solvent extraction plant of the same capacity.

The results identified in Figure 7.1 reveal that to equal the net profitability achievable with the solvent extraction processes examined in the study, the extraction efficiency of the mechanical extraction process would need to be increased to achieve an oil yield of 91.31%, equivalent to a residual oil in cake of 6.1% from rapeseed with an original oil content of 43%.

It should be noted that when calculating the effect of the oil yield on the profitability of the process, the meal price was kept constant at £64.78 per tonne, a price calculated for meal with a residual oil content of approximately 10 %. The premium on the rapeseed meal for the high residual oil content will reduce as the residual oil is lowered, therefore, it is considered that in real terms the actual oil yield required from the mechanical extraction process to equal the net profitability of the solvent plant will be slightly greater than 91.31%.

7.3.2 Meal Price

An investigation was carried out to show how the premium meal price available for the resultant high oil content rapeseed meal from the 1000 MTPD mechanical extraction plant examined in the study effects the profitability of the extraction process. A calculation of the net profitability of the process at a range meal prices was carried out using the processing figures identified in Tables 7.2 and 7.3. By changing only the price available for rapeseed meal in Table 7.2 the effect the meal price has on the profitability of the process could be assessed. The graph in Figure 7.2 identifies the results from the investigation and shows at what premium price for the high oil content meal the mechanical extraction process will match the achievable net profit of a solvent extraction plant of the same capacity.

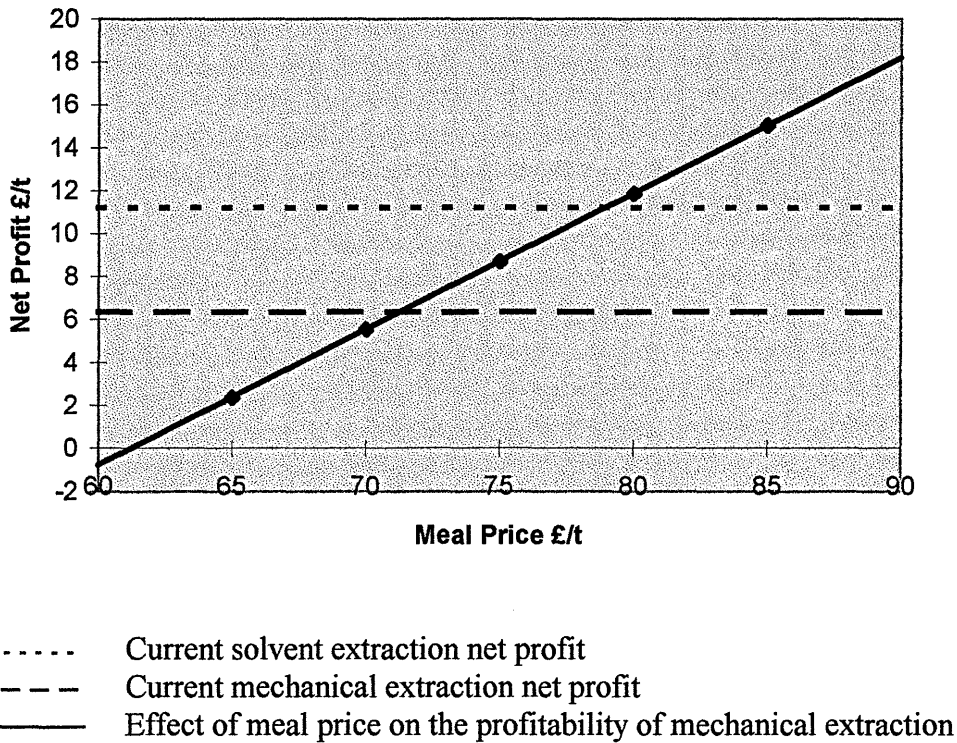


Figure 7.2 The effect the market price of high oil content rapeseed meal from a 1000 MTPD mechanical extraction plant has on the profitability of the process compared to a solvent extraction plant of the same capacity.

The results identified in Figure 7.2 reveal that to equal the net profitability achievable with the solvent extraction process selling rapeseed meal at £64.78 per tonne (as calculated in section 7.2.2.1), the meal price from the mechanical extraction process would need to reach £78.95 per tonne. This figure equates to a £14.17 premium per tonne of meal at an oil content of 9.9%.

These findings are comparative to those of Weber (1997) who states that for a mechanical extraction plant to be as profitable as a solvent extraction plant, it is imperative to get a bonus for the oil content remaining in the cake. Only when there is a market for the meal and the feed mills in the vicinity are prepared to pay a premium price for the meal does the mechanical extraction process become profitable. The bonus price that Weber (1997) states is required per tonne of meal, at 11% oil content, to match the cash flow of a solvent extraction plant is approximately US\$23 which at an exchange rate of US\$1.66 = £1 is equivalent to £ 13.86 per tonne of meal, similar to the Figure £14.17 per tonne of meal previously calculated in this section.

7.3.3 Steam requirement

An investigation was carried out to show how the steam requirement of the preparation process for the 1000 MTPD mechanical extraction plant examined in the study effects the profitability of the extraction process. A calculation to show how savings in steam requirement would effect the net profitability of the mechanical extraction process was carried out using the processing figures identified in Tables 7.2 and 7.3. By changing only the steam requirement figure in Table 7.3 the effect the steam requirement has on the profitability of the process could be assessed. The graph in Figure 7.3 shows the results from the investigation.

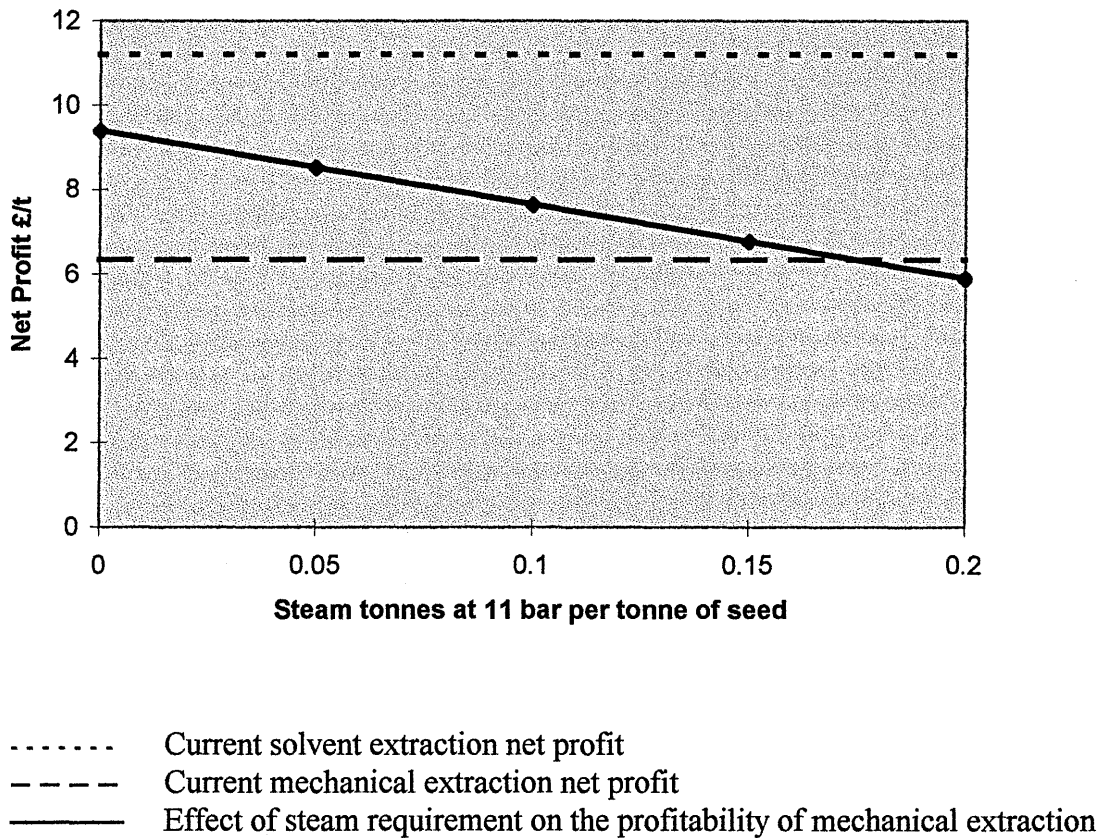


Figure 7.3 *The effect the steam requirement for a 1000 MTPD mechanical extraction plant has on the profitability of the process compared to a solvent extraction plant of the same capacity*

The results identified in Figure 7.3 reveal that no matter to what degree a reduction in steam use in the mechanical extraction process is made, the savings alone will not enable the mechanical extraction process to equal the net profitability achievable with the solvent extraction process. The results show that even if the use of steam was eliminated completely, the solvent extraction plant would still be more profitable by £1.80 per tonne of seed processed than the mechanical extraction plant.

7.3.4 Electricity requirement

An investigation was carried out to show how the electricity requirement of the process equipment of the 1000 MTPD mechanical extraction plant examined in the study effects the profitability of the extraction process. A calculation to show how savings in electricity would effect the net profitability of the mechanical extraction process was carried out using the processing figures identified in Tables 7.2 and 7.3. By changing only the electricity requirement figure in Table 7.3 the effect the electricity requirement has on the profitability of the process could be assessed. The graph in Figure 7.4 shows the results from the investigation.

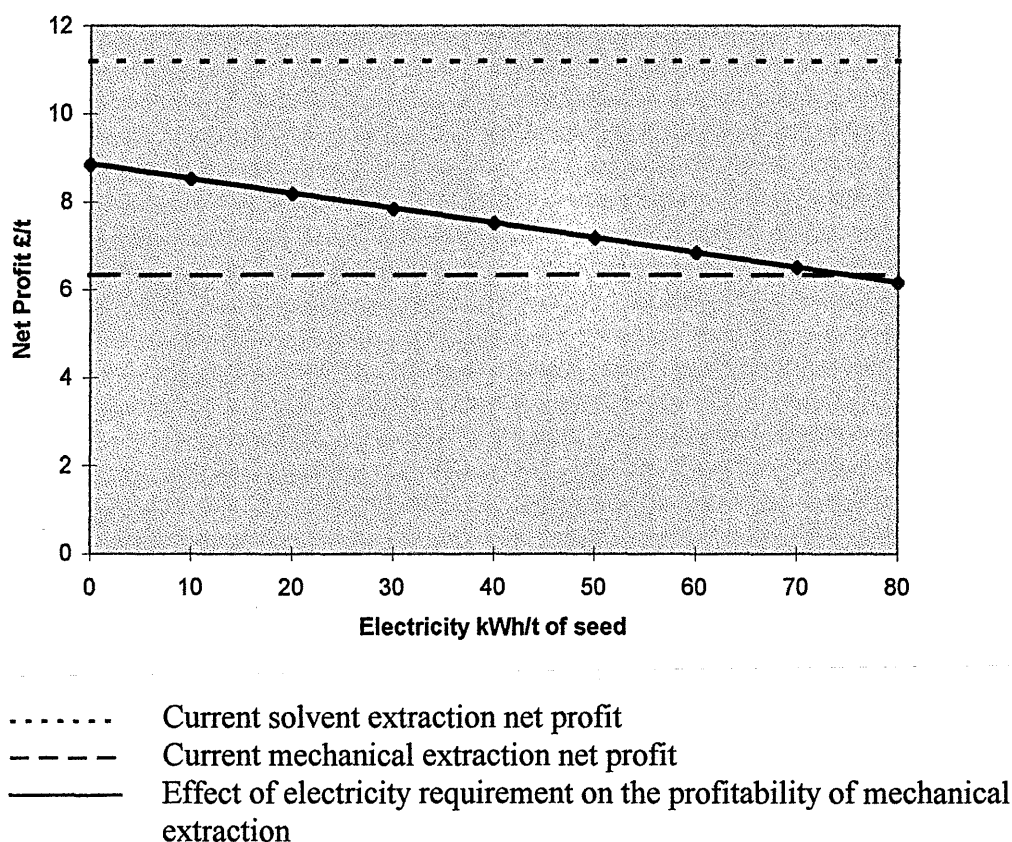


Figure 7.4 The effect the electricity requirement for a 1000 MTPD mechanical extraction plant has on the profitability of the process compared to a solvent extraction plant of the same capacity

The results identified in Figure 7.4 reveal that no matter to what degree electrical savings are made to the mechanical extraction process, the savings alone will not enable the mechanical extraction process to equal the net profitability achievable with the solvent extraction process. The results show that even if the cost of electricity was eliminated completely, the solvent extraction plant would still be more profitable by £2.34 per tonne of seed processed than the mechanical extraction plant.

7.4 Extrusion in oilseed processing

The reasoning for the research was to investigate the possibility of introducing extrusion technology, as a replacement to the current preparation processes of flaking and conditioning, to improve the profitability of a mechanical extraction process. The following section assesses the commercial implications of adopting extrusion technology as a preparation treatment.

7.4.1 Processing economics with the introduction of extrusion

The previous section has identified that a premium price on high oil meal, extraction efficiency, and to a lesser extent the electricity and steam requirement, are all market or processing factors that can determine the profitability of the mechanical extraction process.

The market price for high oil content meal is not controllable by the oilseed processors and is totally dependant on demand from animal feed mills and their willingness to pay a premium price for the product. Meal price has proved to be an important factor in the profitability of the mechanical extraction process, however any improvement achieved within the process efficiency will not increase the revenue obtained from the meal sales.

The introduction of extrusion technology as a preparation treatment could however affect the extraction efficiency and the electricity and steam requirement, all factors that have been identified as significant to the profitability of the mechanical extraction process.

The experimental research discussed earlier in Chapters 5 and 6, investigating the effectiveness of extrusion as a preparation treatment for mechanical extraction of oil, would suggest that there is a possibility that some improvement to the extraction efficiency could be gained from the introduction of extrusion technology. The increase in oil yield will reduce the residual oil content of the meal reducing the premium that can be demanded for the meal. This will have an adverse effect on the revenues from meal sales. The drop in revenue from the meal sales will however be outweighed by the increase in oil production, a considerably higher valued commodity than the meal, resulting in an overall increase in revenue.

The laboratory scale extrusion experiments discussed in Chapter 5 revealed a high level of cell damage to the rapeseed during the extrusion process, a factor that is supported from the analysis of the milling defect on the extruded rapeseed. The analysis revealed that the milling defect of the extruded rapeseed was considerably lower than that of commercial preparation treatments indicating a greater level of preparation.

Although the milling defect of the extruded rapeseed from the large scale extrusion experiments, discussed in Chapter 6, was no lower than that of commercial prepared rapeseed, at optimum processing temperatures the extruded rapeseed did have a lower residual oil in cake following pressing than the simulated commercial preparation of flaking and conditioning.

2?

If the performance of the small scale laboratory extruder to prepare rapeseed for mechanical extraction could be emulated with a commercial scale extruder, then it would be reasonable to assume that an increase in extraction efficiency could be achieved by the introduction of extrusion as a replacement to current commercial preparation treatments.

The introduction of extrusion to replace flaking and conditioning would eliminate the requirement of steam from the mechanical extraction process. The process operating costs shown in Table 7.3 reveal that the steam requirement costs £3.06 per tonne of seed processed, this accounting for almost 30% of the total operating cost. The elimination of steam from the process by the introduction of extrusion would make a significant difference to the profitability of the mechanical extraction process.

The introduction of extrusion technology as a replacement for flaking and conditioning would increase the electricity requirement of the mechanical extraction process. The extrusion process does have a greater electricity demand than the combined flaking and conditioning processes. Although the exact electricity requirement for extruding oilseed has not been made available, it is considered that the electricity demand will be similar to that of operating a press.

The electricity demand for the mechanical extraction process with the introduction of extrusion is calculated by the electricity demand of the press + extrusion + conveyors and pumps etc.- (flaker + conditioner) this figure will amount to approximately 105 kWh per tonne of processed seed, an overall increase in demand of approximately 30 kWh per tonne of seed. There is however a possibility that with the increase in electricity demand of the processing plant, the cost of electricity per unit from the utility suppliers may be reduced.

The economics of the mechanical extraction of rapeseed oil with extrusion as a preparation treatment has been investigated to reveal the estimated investment costs, operating costs and potential profits of the new process.

7.4.1.1 Investment cost

An estimation of the overall investment costs, together with a breakdown of the individual equipment costs, not including installation, has been determined for a mechanical oil extraction plant with high pressure single screw extrusion seed preparation. The investment costs for the processing plant is shown in Table 7.7.

Table 7.7 *The overall investment requirement and a breakdown of the equipment costs for a 1000 MTPD mechanical oil extraction plant with extrusion as a preparation treatment.*

Mechanical Extraction with Extrusion	
Total investment cost (£)¹	7,225,000
Equipment cost (£)²	
Press ³	
pre-presses	500,000
second press	2,000,000
Extruders	2,000,000
Conveyors and pumps etc. ⁴	675,000
Total Equipment Cost (£)	5,175,000

¹ The total investment cost includes the equipment, installation and the cost of buildings.

² The equipment cost does not include installation.

³ A manufacturer of screw presses stated that a press specification capacity of 500 MTPD is quoted as a pre-press capacity. The capacity of the press being used for a second high pressure press is reduced to approximately 100 - 125 MTPD, therefore, four second presses are required to match the throughput of each pre-press. The investment cost required for the presses has therefore been based on the purchase of 10 x 500 MTPD screw presses.

⁴ An equipment manufacturer suggested that a guide for the calculation of the investment requirement for the materials handling equipment (conveyors and pumps) is 15% of the total equipment investment, this figure has therefore been used in the calculation of investment for the extraction processes.

7.4.2 Processing economics

The economics of rapeseed oil extraction for a mechanical extraction plant with extrusion has been investigated to identify the estimated production efficiency and operating costs, along with the potential profits of the process. The potential profits have been estimated for two production scenarios, firstly assuming that the extraction process with extrusion has the same oil yield as conventional mechanical oil extraction, and secondly, that the extraction process with extrusion produces a higher oil yield than conventional mechanical oil extraction. The results of the investigation are presented below.

7.4.2.1 Gross profit

The revenue and gross profit of the mechanical extraction process with extrusion as a preparation treatment was calculated in the same way as for the current mechanical and solvent extraction processes discussed in Section 7.2 enabling a direct comparison between the processes to be made. The results of the investigation is shown in Table 7.8.

Table 7.8 *The calculated potential revenue and gross profit per tonne of processed rapeseed for a 1000 MTPD mechanical oil extraction plant with extrusion as a preparation treatment.*

Mechanical Extraction with Extrusion			
	No increase in oil yield		Increase in oil yield
Extraction efficiency			
Seed (kg)	1000		1000
Yield (%) ¹	85.5		90
Oil extracted (kg)	367.65		387
Meal (kg)	632.35		613
OIC (%)	9.9		7.0
Product cost			
Seed cost (£/t)	125		125
Oil price (£/t)	263		263
Meal price (£/t) ²	71.25		64.78
Revenue			
Oil (£ per t of seed)		96.69	101.78
Meal (£ per t of seed)		45.05	41.61
Total		141.74	143.34
Seed (£/t)	125		125
Gross profit (£/t)		16.75	18.39

¹ An oil yield of 90% was considered as a realistic figure that could be achieved by the introduction of extrusion as a replacement to current commercial preparation treatments.

² Meal price with an increase in oil yield was calculated based on a 50% reduction on the oil premium currently available on high oil content meals from current mechanical extraction due to the reduction in the residual oil from 10% to 7% with the introduction of extrusion as a preparation treatment.

7.4.2.2 Operating cost

The major operating costs for the mechanical extraction processing plant with extrusion has been investigated to enable the net operating profit of the plant to be calculated. Table 7.9 shows the calculated operating cost and net profit per tonne of processed rapeseed.

Table 7.9 *The calculated operating cost and net profit per tonne of processed rapeseed for a 1000 MTPD mechanical oil extraction plant with extrusion as a preparation treatment.*

Mechanical Extraction with Extrusion		
Consumable		
<i>Electricity</i> ¹	<i>(kWh per t of seed)</i>	
Extrusion		40
Pressing		55
Conveyors and pumps		10
etc.		
<i>Total (kWh/t)</i>		<i>105</i>
<hr/>		
Variable cost		<i>(£/t)</i>
Electricity (£/kWh) ²	0.0336	3.53
<i>Total Variable Cost</i>		<i>3.53</i>
<hr/>		
Semi variable cost		<i>(£/t)</i>
Maintenance (£) ³		3.5
Personnel ⁴	20	
Salary per annum £ ⁵	20,000	1.3
<hr/>		
	No increase in oil yield	Increase in oil yield
Gross profit (£/t)	16.75	18.39
Operating cost (£/t)	8.36	8.36
Net profit (£/t)	8.39	10.03

¹ The breakdown of the electrical energy requirement for each stage of the oil preparation, oil extraction and materials handling for the oil extraction process examined was calculated from information provided by a large European oil processing equipment manufacturer and supplier, and from a published paper by Stroup (1997) with the exception of extrusion, which was based on the assumption that the extrusion process would have a similar electrical demand to the secondary press process.

² The cost of electricity is calculated from information of electricity charges quoted in a telephone conversation with a representative of Eastern Electricity plc. business tariffs, and is based on the demand of a current mechanical extraction process. The actual unit cost quoted in Table 7.9 could possibly be slightly lower due to a cheaper rate because of the higher demand with the introduction of extrusion.

³ No specific information on maintenance cost was available for a mechanical oil extraction process however an analysis of the operating cost of a solvent extraction soybean plant was carried out by a large European oil processing equipment manufacturer and supplier. The maintenance cost stated in the analysis of operating cost for the soybean plant was therefore used for the purpose of this study.

⁴ The cost of personnel to operate the extraction plants was not made available from the oilseed processors questioned therefore an annual cost of £20,000 per person was assumed for the purpose of the study. An assumption was made that the personnel requirement for a mechanical extraction process with extrusion was the same as a current mechanical extraction process.

7.4.3 Annual profit

The annual profit that can be achieved from a mechanical extraction rapeseed processing plant with extrusion for the two processing efficiency scenarios examined has been calculated and the results shown in Table 7.10.

Table 7.10 *The comparison of the calculated annual profit for a 1000 MTPD mechanical oil extraction plant with extrusion.*

		Mechanical Extraction with Extrusion	
		No increase in oil yield	Increase in oil yield
Investment (£)		7,225,000	7,225,000
Capacity MTPD	1000		
Annual days of operation	330		
Yearly capacity	330,000		
Net Profit (£/t)		8.39	10.03
Annual operating profit (£)		2,768,700	3,309,900

The results show that the annual operating profit achievable from a mechanical extraction plant with extrusion for the two production efficiency scenarios examined show that an increase in oil yield from 85.5% to 90% significantly increases the achievable annual operating profit for the process. It should be noted that the calculation of the annual operating profit shown in Table 7.10 only took into consideration the extraction plant operating costs that could be directly attributed to the extraction process. The calculation does not include costs additional to the extraction process that would be associated with an oil extraction business such as managerial, sales and administration costs or plant and personnel insurance etc.

The calculation of the annual profit for the two extraction plants was also based on the scenario that the plant would be operating at full capacity for 330 days a. year. Any disruption to the process, such as downtime for repairs and service of equipment, would result in a decrease plant throughput and reduce the obtainable revenue. The actual profit from the oil extraction process would then be less than the figure identified in Table 7.10.

7.5 Conclusion of economic comparison

The results of the economic study for each of the 4 processing scenarios investigated have been summarised in Table 7.11 enabling a direct comparison of investment requirements and expected profitability for each of the processes.

Table 7.11 *The comparison of processing economics for each of the 1000 MTPD rapeseed processing scenarios investigated.*

	Mechanical Extraction	Solvent Extraction	Mechanical Extraction with Extrusion	
			No increase in oil yield	Increase in oil yield
Total investment cost (£)	6,600,000	10,000,000	7,225,000	7,225,000
Equipment cost (£)	4,554,000	5,129,000	5,175,000	5,175,000
Gross profit (£/t)	16.75	23.74	16.75	18.39
Operating cost (£/t)	10.42	12.55	8.36	8.36
Net profit (£/t)	6.33	11.19	8.39	10.03
Annual operating profit (£)	2,088,900	3,692,700	2,768,700	3,309,900

A comparison in the investment cost between the traditional mechanical extraction plant and a mechanical extraction plant with extrusion as a preparation shows that the introduction of extrusion will produce approximately a 10% increase in investment cost. The mechanical extraction process with extrusion will still however require far less investment capital than a solvent extraction plant.

A comparison in the gross profit per tonne of processed rapeseed, calculated for current 1000 MTPD mechanical and solvent oil extraction process, and a mechanical extraction process with extrusion as a preparation, revealed that with an increase in oil yield with the new process the gross profit with the introduction of extrusion is approximately £1.5 per tonne of processed seed greater than with a current mechanical extraction plant, however is still approximately £5.5 per tonne of processed seed less than achievable with a solvent extraction plant.

A comparison in the net profit per tonne of processed rapeseed, calculated for a current 1000 MTPD mechanical oil extraction process and a mechanical extraction process with extrusion as a preparation, revealed that with commensurate oil extraction efficiencies the process with the introduction of extrusion provides a greater net profit by approximately £2 per tonne of processed seed. If the predicted increase in the oil extraction efficiency for the process with the introduction of extrusion occurred, a further increase in the net profit would be achieved making the net profit for the new process approximately £4 per tonne of processed seed greater than with the traditional mechanical extraction process.

The investigation does however reveal, that even for the best case scenario for a mechanical extraction plant with extrusion as seed preparation, the net profit per tonne of processed seed is still approximately £1 per tonne less than with the solvent extraction plant.

8. SUMMARY OF RESEARCH

8.1 Introduction

Chapter 8 summarises, compares and discusses the findings from the set of laboratory scale Brabender extrusion experiments, the large scale Almex extruder set of experiments and the study of processing economics.

8.2 Extrusion experiments

The laboratory scale Brabender extruder experiments, discussed in Chapter 5, permitted a comprehensive investigation of a wide range of extrusion variables and process operating conditions to assess the effectiveness of extrusion as a preparation treatment for the pressing of rapeseed, and how the individual operating variables and conditions affect the process.

The findings from the investigation identified that the Brabender extruder was effective as a preparation for the rapeseed. At the optimum operating conditions the extrusion process was effective in breaking virtually every seed with a high level of cell damage apparent from the analysis of the rapeseed microstructures.

The rapeseed moisture content and each of the extruder operating variables investigated in the experiments all proved to be significant factors in the performance of the extrusion process as a preparation treatment. The investigation also revealed that of the process variables assessed, the rapeseed moisture content and the extruder processing temperature appeared to have the greatest impact on the effectiveness of the process.

At the optimum processing conditions the analysis of the residual oil content in the rapeseed cake following extrusion and pressing in a hydraulic ram press revealed a relatively high oil yield. The lowest percentage residual oil in cake following pressing was 9.37% which represents an oil extraction efficiency of 78%. This extraction efficiency is considered good with a ram press which is generally less efficient than a screw press.

The analysis of the milling defect of the extruded rapeseed also confirmed the effectiveness of the extrusion process as a preparation treatment for rapeseed. The milling defect is commonly used in the oil processing industry to give a numerical figure representative of the work done to an oilseed at different stages of the extraction process. A low milling defect value represents a high level of work done on the seed. In a commercial oil processing plant a prepared rapeseed sample would be expected to have a milling defect value of between 3 and 5. The milling defect values for the rapeseed samples extruded with the Brabender extruder ranged between 0.7 and 3.5, the majority considerably lower than those expected in a commercial oil extraction plant.

The optimum processing conditions identified in the laboratory scale Brabender extrusion experiments were a moisture content of 7.5% with a processing temperature not higher than 80°C. It was also identified that it is not necessary to use a screw compression ratio in excess of 3:1 for processing rapeseed at temperatures below 80°C.

The larger scale Almex extrusion experiments, discussed in Chapter 6, permitted a wider range of process temperatures to be investigated and a comparison of the process with the traditional preparation treatments of flaking and conditioning. The experiments also enabled a comparison between the small laboratory Brabender extruder and the larger Almex extruder to assess how the scale of the extruder affects the process performance.

The findings of the Almex trials, as with the Brabender trials, revealed that at processing temperatures below 80°C and above 0°C the extrusion process did break the majority of the seeds processed and the analysis of the extruded rapeseed microstructures revealed a large degree of cell structure damage.

The optimum extrusion processing temperature for the Almex extruder was identified at 40°C. At this temperature the analysis of the residual oil content in the rapeseed cake following extrusion and pressing in a screw press, revealed an oil yield comparable to that of the simulated traditional preparation treatment assessed. The mean oil yield at extrusion temperature 40°C was 12.64% after a first press and 11.42% following a double press, this representing an extraction efficiency of 70% and 73% respectively. This extraction efficiency is equivalent to the yield that is claimed by the press manufacturer as achievable with the Mini 100 screw press used in the experiments.

The analysis of the milling defect value of rapeseed extruded at 40°C was 4.71 which is comparable to the figure that would be expected from prepared rapeseed in a commercial extraction plant.

Problems with oil saturation were encountered with both sets of extrusion experiments and can cause reduced and inconsistent throughput of the extruder.

The analysis of the results from the two sets of extrusion experiments revealed that the performance of the extrusion process as a preparation treatment reduced with a scaling up in size of operation. The machine tolerances are greater on larger machines and a higher number of seeds are left undamaged during the extrusion operation. The set of the laboratory scaled Brabender extrusion trials revealed a greater percentage of cell structure damage, lower milling defect values and greater process extraction efficiency than the larger scale Almex trials.

8.3 Processing economics

An investigation was carried out to compare the processing economics for 1000 MTPD rapeseed mechanical and solvent oil extraction plants. The investigation revealed that the solvent extraction process was considerably more profitable than the mechanical extraction process. The study also identified that the percentage oil yield, meal price and, to a lesser extent, the energy demand of the process were all major factors concerning the profitability of a mechanical extraction plant.

The premium price that can be demanded for high oil content meal from mechanical extraction plants is dependent on demand for the meal from animal feed mills, and if the feed mills consider there is added value to them from the high oil. The achievable meal prices are beyond the control of the processors and not directly related to the oil extraction process. The oil yield and energy demand can however be influenced by the oil processor and can be significantly affected by the rapeseed preparation treatment.

Two scenarios were developed to assess the effect on the profitability of a mechanical oil extraction plant by introducing extrusion as a replacement preparation treatment to milling and conditioning currently used in the mechanical extraction process. The first scenario assumed that the preparation performance achieved with the small scale Brabender extruder could be emulated within a commercial scale plant resulting in the mechanical process achieving a greater oil yield than currently attainable. The second scenario assumed that the introduction of extrusion to the mechanical extraction process had no effect on the achievable oil yield.

The investigation revealed that with an increase in oil yield with the introduction of extrusion, coupled with the increased energy efficiency achieved by the elimination of the steam requirement by removing conditioning from the process, would result in an increase in profitability nearing that attainable with a solvent extraction process.

The second scenario revealed that even if there was no improvement in the oil yield with the introduction of extrusion to the mechanical process the increase in energy efficiency realised with the introduction of extrusion would increase the achievable profit by approximately £2 per tonne of processed seed.

8.4 Conclusions from summary

The initial hypothesis stated in Chapter 1, that “an efficient and industrially competitive process to extract a high quality crude vegetable oil from rapeseed, with a resultant oil in cake content of 3%, can be achieved without the use of a solvent extraction process” has not been achieved with the introduction of extrusion to the mechanical extraction process.

The results from the extrusion experiments using the small scale Brabender laboratory extruder did however suggest that there was some potential benefit to be gained from using extrusion technology in the preparation of rapeseed for mechanical extraction of oil, however, a reduction in processes extraction efficiency was apparent with a scaling up of the extraction process using the larger scaled Almex extruder.

A conclusion drawn from the research is that with current extrusion technology the introduction of extrusion to a commercial scale processing plant will not improve the oil yield of the process sufficiently to make the mechanical extraction process commercially competitively against a current solvent extraction plant. The process will only become a viable alternative to solvent extraction if future advancements in large scale extruder design can achieve the preparation efficiency attainable with laboratory scale extrusion.

9. CONCLUSIONS

The following conclusions were drawn based on the findings of this research.

1. Extrusion experiments with a laboratory scale Brabender single screw extruder suggest that there is a potential for extrusion technology to provide a more effective preparation treatment for rapeseed than the milling and conditioning processes currently used commercially for the mechanical extraction of oil.
2. Rapeseed moisture content, extruder barrel temperature, screw speed, die size and screw compression ratio are all significant processing variables for the preparation treatment of rapeseed with an extruder.
3. At a barrel temperatures of 80°C, no advantage to the preparation treatment is gained from increasing the screw compression ratio above 3:1.
4. The optimum extrusion processing variables identified in the laboratory scale trials that achieve the most effective preparation treatment are rapeseed moisture content 7.5%, barrel temperature no greater than 80°C, a screw compression ratio of 3:1, a screw speed no greater than 90 rev/min with a 19 mm screw Ø and a die size between 5 and 6 mm Ø. These process variables will also provide the lowest extruder power requirement, however, to achieve maximum machine throughput the screw speed must be increased to at least 150 rev/min.
5. The findings from both the Brabender and Almex extrusion trials revealed that at processing temperatures below 80°C and above 0°C the extrusion process broke the majority of the seeds processed and the analysis of the extruded rapeseed microstructures revealed a large degree of cell structure damage.

6. The larger scale Almex extrusion experiments revealed that the greatest damage to the cell structure and the lowest milling defect value both occurred following extrusion at a barrel temperature of 40°C.
7. The milling defect of rapeseed extruded at a barrel temperature of 40°C was lower than that of the simulated traditional preparation treatment of flaking and conditioning.
8. Analysis of the residual oil in the press cake following both extrusion with the Almex extruder and a double press, and simulated traditional preparation treatments and a double press, revealed the greatest extraction efficiency occurred following extrusion at barrel temperatures of 0 and 40°C. There was no significant difference in the residual oil in the press cake following a double press between extruder barrel temperatures 0 and 40°C.
9. The predicted optimum extrusion variables for a commercial scale extrusion preparation treatment are barrel temperatures 40°C, compression ratio 3:1 and seed moisture content 7.5%.
10. The results from the two sets of extrusion experiments revealed that the performance of the extrusion process as a preparation treatment reduced with a scaling up in size of operation. The laboratory scaled Brabender extrusion trials revealed a greater percentage of cell structure damage, lower milling defect values and greater process extraction efficiency than the larger scale Almex trials.
11. The percentage oil yield, meal price and, to a lesser extent, the energy demand of the process were all major factors concerning the profitability of a mechanical extraction plant.

12. With current extrusion technology the introduction of extrusion to a commercial scale processing plant will not improve the oil yield of the process sufficiently to make the mechanical extraction process commercially competitively against a current solvent extraction plant. The process will only become a viable alternative to solvent extraction if future advancements in large scale extruder design can achieve the preparation efficiency attainable with laboratory scale extrusion.
13. If the preparation performance achieved with the small scale Brabender extruder could be emulated within a commercial scale plant, it is considered that the introduction of extrusion as a preparation treatment would increase the extraction efficiency of the process. The increase in oil yield, together with the elimination of the steam requirement from the process achieved from the elimination of conditioning from the preparation process, would increase the profitability of the mechanical extraction process nearing that of a solvent extraction plant. The net profit would increase from £6.33/t for current mechanical extraction to £10.03/t with the introduction of extrusion, but this is still less than £11.19/t achievable with solvent extraction.

10. RECOMMENDATIONS FOR FURTHER RESEARCH

1. Carry out a set of extrusion trials on a commercial scale to enable a direct comparison of extraction efficiency between two methods of preparation treatment
 - a) extrusion, and
 - b) flaking and conditioning.
2. Investigate extruder design to improve the seed preparation performance of a large scale extruder to match that achieved by a laboratory scale extruder. Areas on which to concentrate design should be screw and barrel design in order to incorporate higher rates of shear within the extruder barrel, and drainage of oil at the feed end of the extruder barrel.

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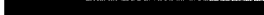
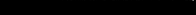
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Appendix A

Work schedule for 4 year EngD programme

The work schedule for the 4 year EngD programme, shown overleaf, identifies the major stages of the research programme showing the planned start and finish time for each of the stages.

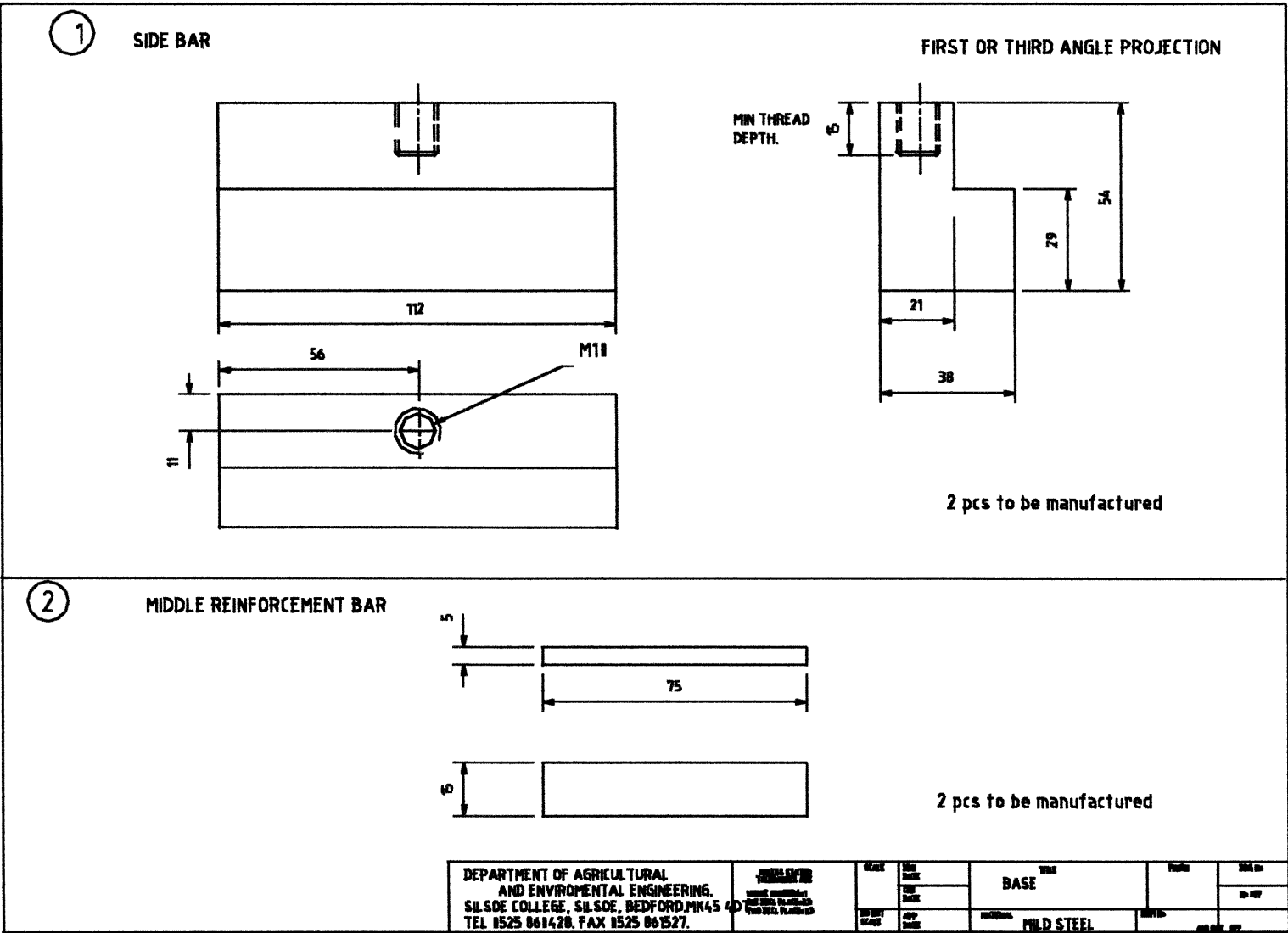
	Oct95-Mar96	Apr 96-Sep96	Oct96-Mar97	Apr97-Sep97	Oct97-Mar98	Apr98-Sep98	Oct98-Mar99	Apr99-Oct99
Management Training								
Initial Project Proposal								
Literature Review								
Research Proposal								
Lab. Scale Experiments								
Analysis of Results								
Large Scale Experiments								
Analysis of Results								
Commercial Viability Study								
Write Up Period								

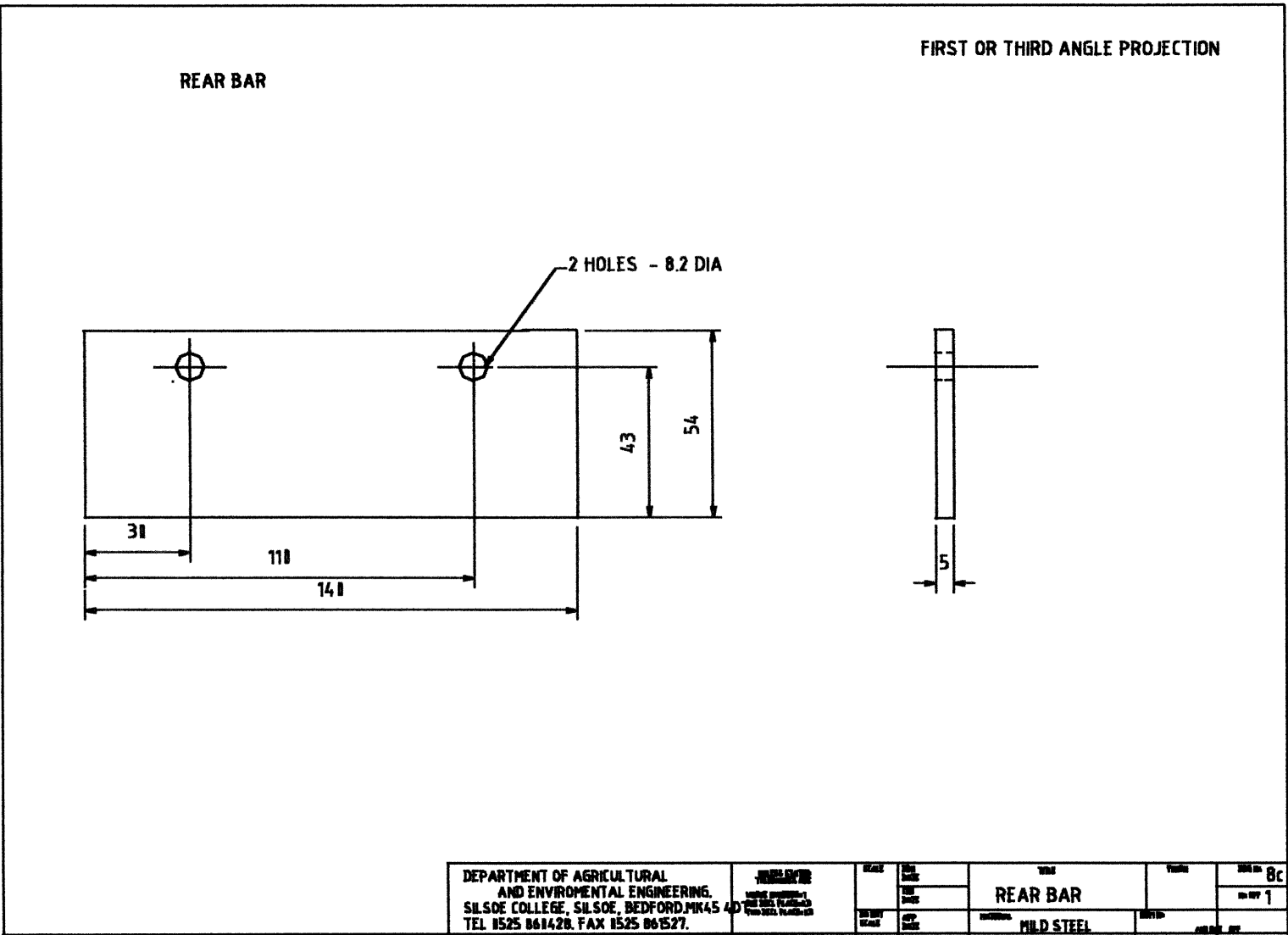
Appendix B

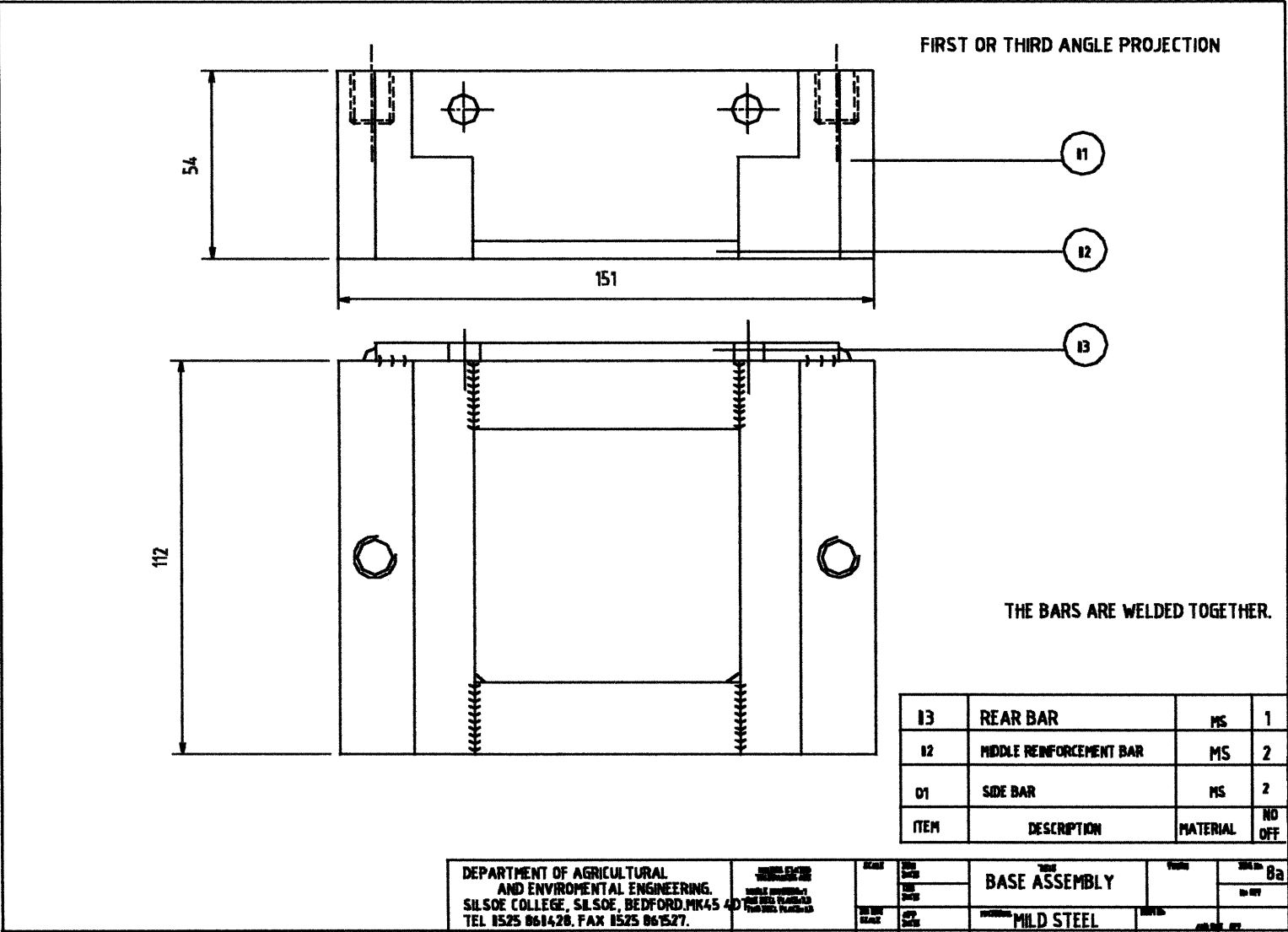
Engineering drawings of the ram press used for the laboratory scale extrusion experiments

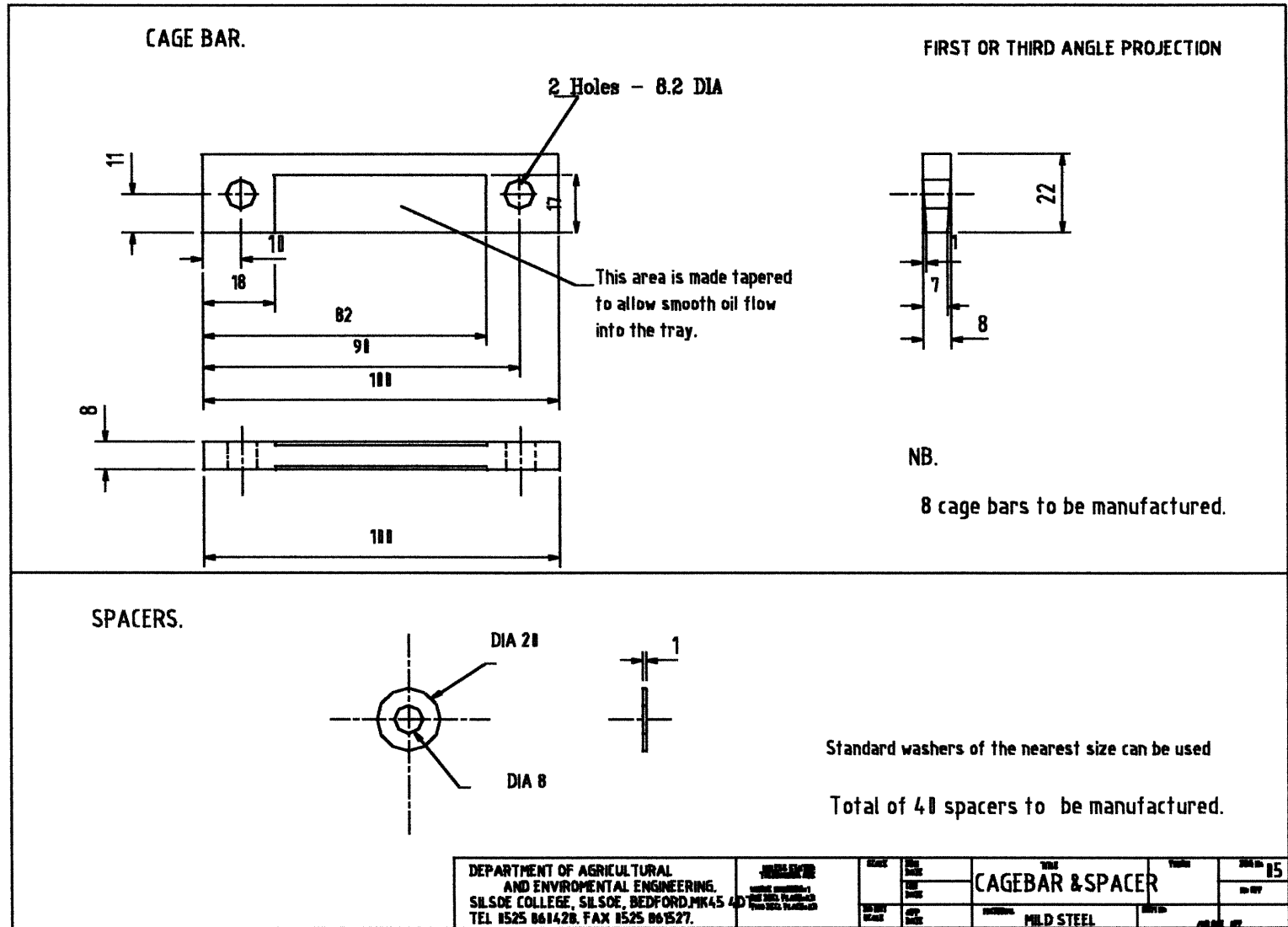
Drawing 1	Assembly drawing of ram press
Drawing 2	Press base
Drawing 3	Base rear bar
Drawing 4	Base assembly
Drawing 5	Cage bar
Drawing 6	Barrel
Drawing 7	Barrel brackets
Drawing 8	Barrel assembly
Drawing 9	Piston
Drawing 10	Oil tray

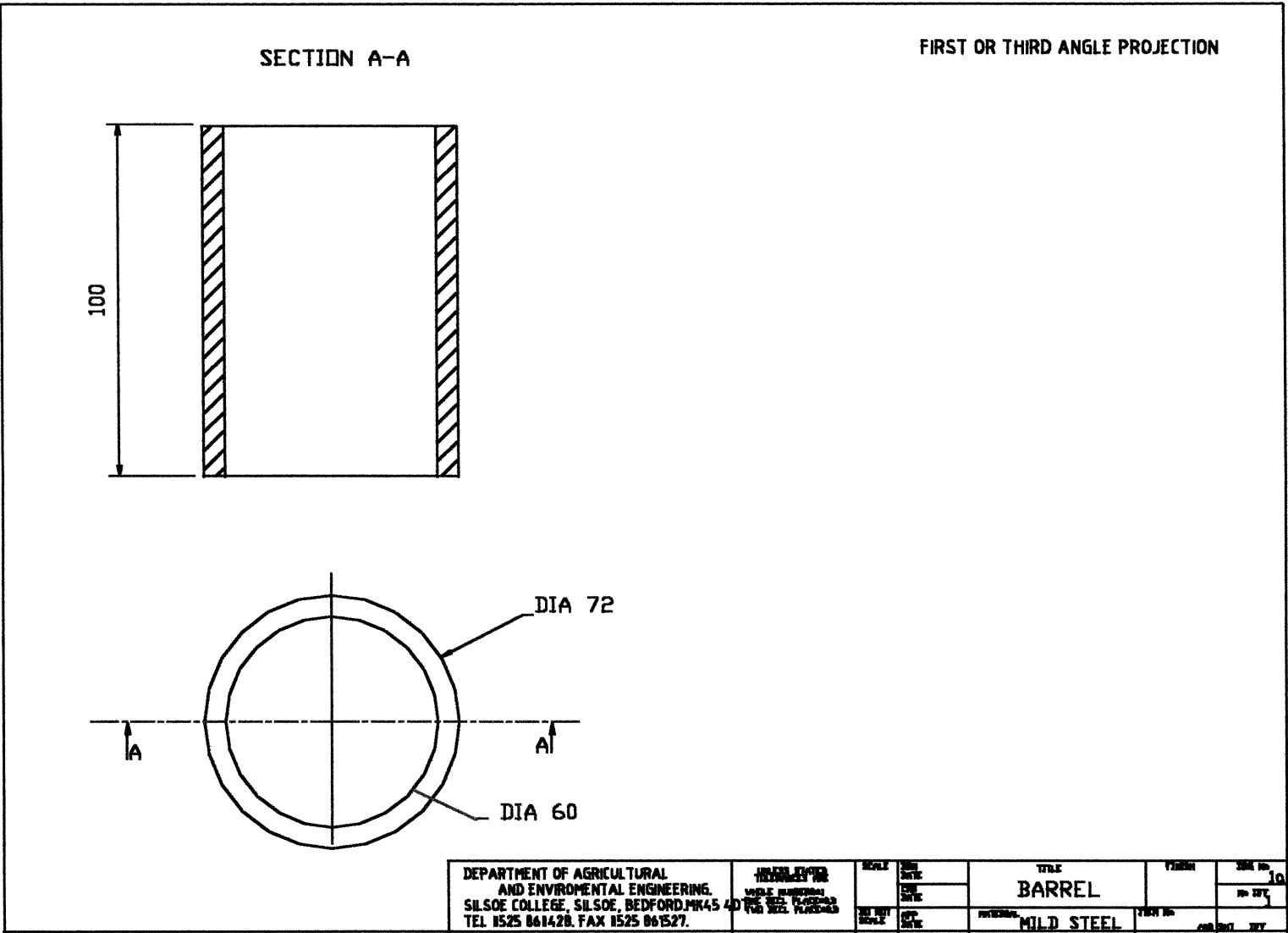


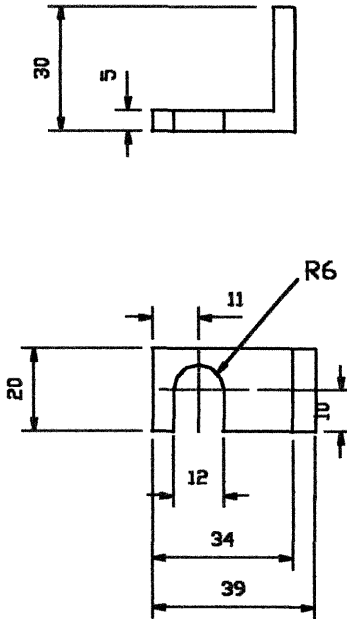










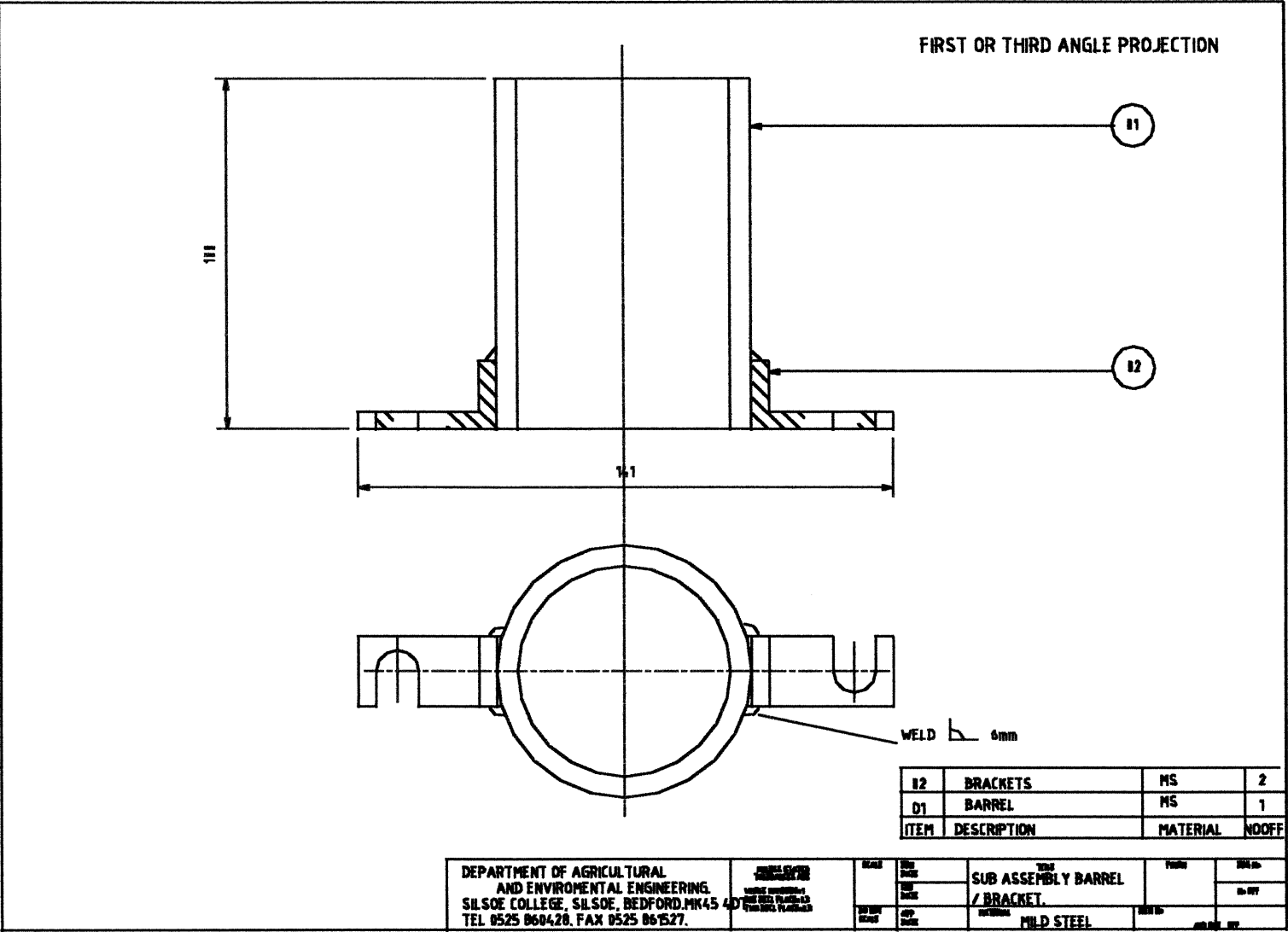


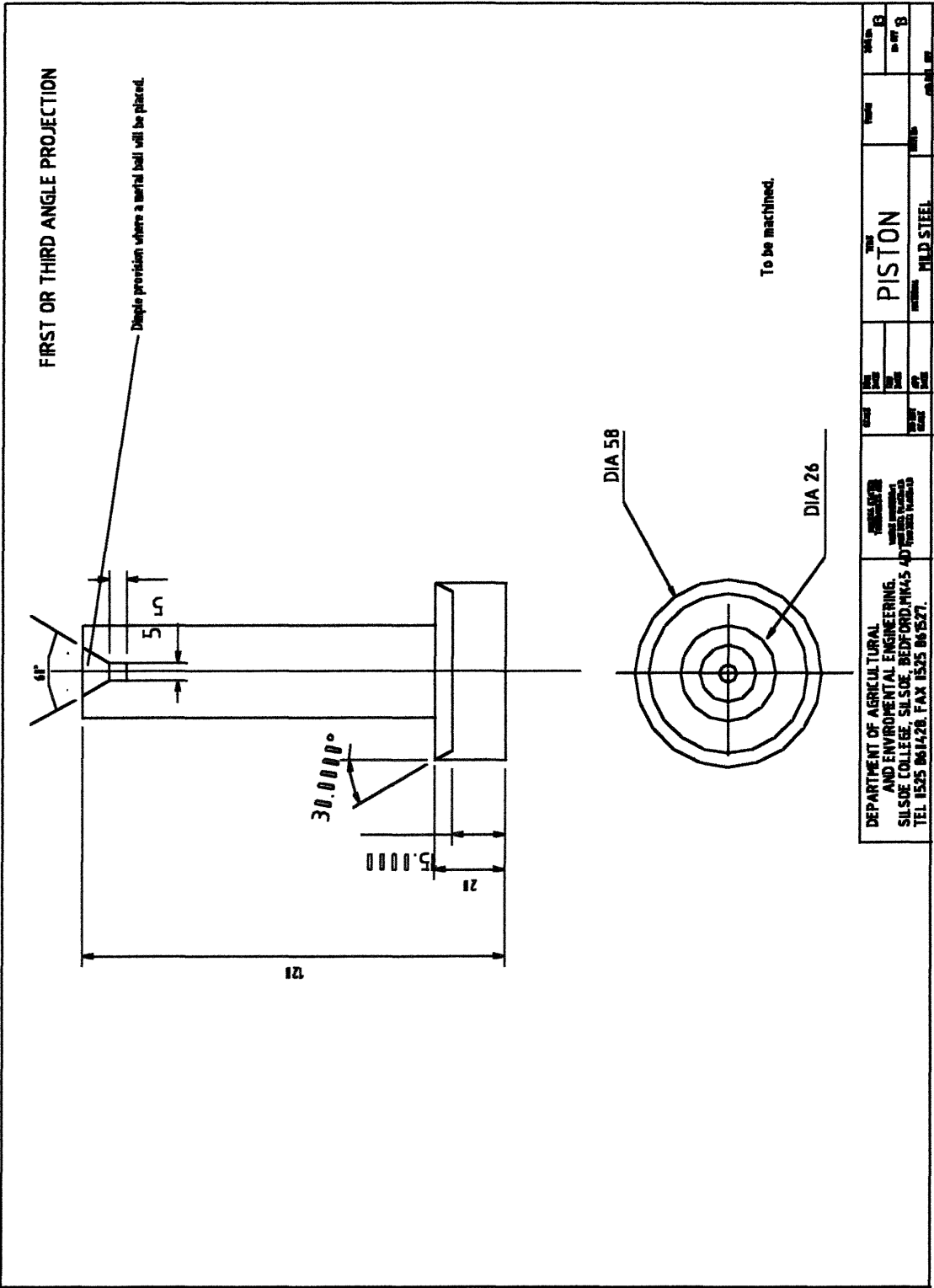
FIRST OR THIRD ANGLE PROJECTION

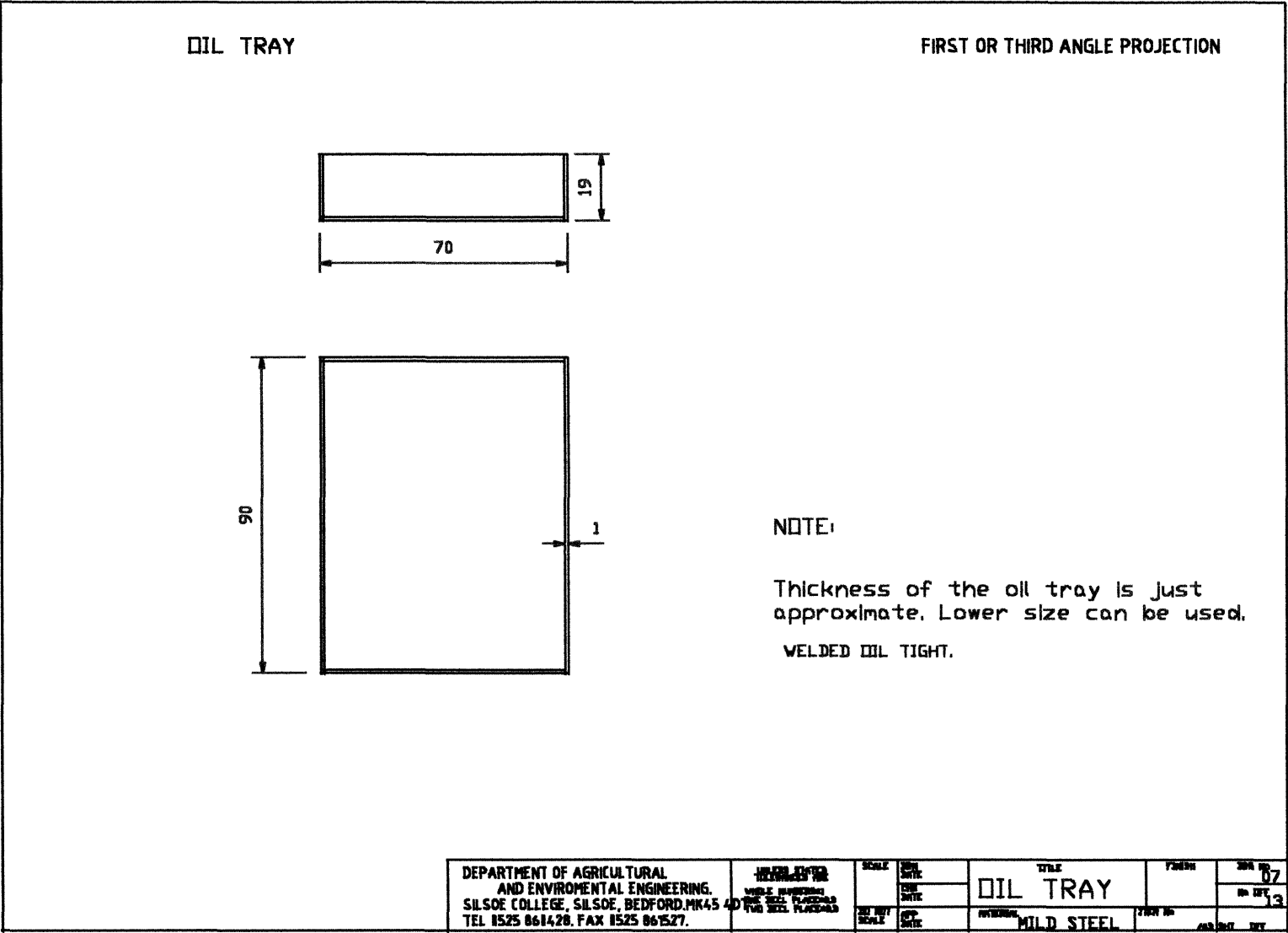
NB:
MAKE FROM 50x50x5 ANGLE IRON.

Two brackets to be manufactured
and welded on the barrel.

DEPARTMENT OF AGRICULTURAL AND ENVIRONMENTAL ENGINEERING. SILSOE COLLEGE, SILSOE, BEDFORD MK45 4DT TEL 0525 861428. FAX 0525 861527.		DESIGN BY DATE CHECKED BY DATE APPROVED BY DATE		TITLE BRACKETS.		MATERIAL MILD STEEL		DRAWN BY DATE		SCALE 1:1	







Appendix C

Extrusion / press interval trial

The trial was carried out identify if the time period between extrusion and pressing had an effect on press performance. An extruded sample was sealed in a container and held at 70°C in an oven. 50g samples of the extrudate were pressed at time intervals 0.5 hr, 1 hr, 2.5 hr and 3 hr from the time of extrusion.

Table showing the effect on pressing efficiency due to time interval between extrusion and pressing.

	Extrusion / Press interval	% Oil in cake
T1	0.5 hr	12.70
T2	1.0 hr	12.86
T3	2.5 hr	13.03
T4	3.0 hr	12.70
Average		12.82
Standard Deviation		0.157

Extrusion variables used for extruder / press interval trial

Compression ratio	4:1
Shaft speed	90rev/min
Die size	5 mm
Temperature	100°C

Appendix D

Results table for laboratory experiment 1. The effect rapeseed moisture content has on the preparation efficiency of the extruder

Process Variables					Results		
Moisture Content %	Temp. °C	Screw Speed rev/min	Die Size mm	Comp. Ratio	OIC Extruded %	OIC Pressed %	Process Efficiency %
10.1	70	90	5	4:1	27.51	14.86	65.16
7.7	70	90	5	4:1	26.51	12.20	71.40
6.1	70	90	5	4:1	33.17	13.36	68.67
4.5	70	90	5	4:1	28.68	16.19	62.04
4.1	70	90	5	4:1	28.18	16.53	61.26
2.8	70	90	5	4:1	41.83	21.19	50.34
2.5	70	90	5	4:1	37.50	23.02	46.04

Appendix E

Results table for laboratory experiment 2. The effect of extrusion temperature on the microstructure of extruded rapeseed.

Process Variables					Results
Moisture Content %	Temp. °C	Screw Speed rev/min	Die Size mm	Comp. Ratio	OIC Extruded %
7	115	100	7	4:1	24.68
7	135	100	7	4:1	28.01
7	155	100	7	4:1	33.56
7	175	100	7	4:1	36.33

Appendix F

Results table and statistical analysis for laboratory 3 The effect extrusion variables have on the efficiency of the process as a preparation treatment. - Residual oil analysis

Results table - Residual oil analysis

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Extruded %OIC	Pressed %OIC	Extraction efficiency (%)
1	80	150	7	5	21.19	12.37	71.01
2	100	150	7	5	23.35	12.86	69.84
3	140	90	5	3	32.34	16.36	61.65
4	100	90	5	4	22.35	12.70	70.23
5	140	90	6	4	32.51	16.03	62.43
6	80	120	7	5	27.84	12.86	69.84
7	120	120	5	5	26.01	13.53	68.28
8	80	120	7	4	34.84	12.53	70.62
9	100	120	5	3	24.52	13.70	67.89
10	80	150	5	5	20.02	12.86	69.84
11	140	90	7	3	34.84	17.03	60.09
12	80	90	6	5	29.01	12.03	71.79
13	80	90	7	4	28.68	11.53	72.97
14	80	120	7	3	22.52	11.70	72.58
15	140	90	6	3	37.66	19.36	54.63
16	80	150	6	3	23.85	13.03	69.45
17	140	120	5	4	35.33	18.86	55.80
18	120	90	7	4	27.51	13.20	69.06
19	140	150	5	4	34.00	18.36	56.97
20	80	120	5	4	25.85	11.53	72.97
21	80	90	7	3	23.35	10.70	74.92
22	120	150	6	5	27.01	13.03	69.45
23	140	90	7	4	34.34	19.86	53.46
24	120	120	5	4	30.84	14.20	66.72
25	100	120	6	5	20.85	11.53	72.97
26	120	120	7	3	34.50	15.36	63.99
27	80	90	6	4	28.34	10.87	74.53
28	100	120	5	5	20.69	11.03	74.14
29	140	120	6	4	33.84	17.53	58.92
30	120	90	6	4	25.68	14.03	67.11

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Extruded %OIC	Pressed %OIC	Extraction efficiency (%)
31	80	120	6	3	26.51	10.87	74.53
32	80	150	7	4	20.02	12.70	70.23
33	100	150	5	4	24.68	12.53	70.62
34	100	150	6	3	29.18	13.03	69.45
35	140	150	5	5	33.84	17.03	60.09
36	100	120	6	4	23.52	12.37	71.01
37	80	150	6	4	21.02	12.70	70.23
38	80	90	6	3	22.35	12.70	70.23
39	80	120	6	4	22.52	10.37	75.70
40	80	150	6	5	23.35	10.87	74.53
41	120	150	5	3	37.33	13.36	68.67
42	80	120	5	5	20.35	10.37	75.70
43	100	90	6	4	22.68	11.70	72.58
44	80	90	5	3	21.02	9.37	78.04
45	100	90	6	5	19.52	10.87	74.53
46	100	150	6	5	28.34	11.70	72.58
47	120	150	5	5	32.01	14.86	65.16
48	80	90	5	5	17.86	9.70	77.26
49	100	120	6	3	32.67	14.70	65.55
50	140	120	7	5	32.01	17.69	58.53
51	100	90	6	3	27.35	13.70	67.89
52	120	120	6	3	34.84	17.53	58.92
53	120	150	7	4	36.33	16.53	61.26
54	140	120	7	4	37.17	19.52	54.24
55	140	150	5	3	39.83	18.36	56.97
56	120	90	5	4	25.68	13.20	69.06
57	80	120	6	5	20.02	10.87	74.53
58	100	150	7	4	30.17	14.20	66.72
59	120	90	5	5	20.35	12.20	71.40
60	100	120	5	4	25.68	12.53	70.62
61	140	90	5	5	25.51	14.36	66.33
62	140	150	6	5	35.50	17.86	58.14
63	120	150	7	3	34.50	18.02	57.75
64	100	90	5	3	24.35	12.37	71.01
65	120	90	7	3	28.51	14.20	66.72
66	80	150	7	3	29.68	11.20	73.75
67	100	90	7	4	23.52	11.53	72.97
68	100	120	7	4	30.17	12.86	69.84
69	100	90	7	3	25.02	11.53	72.97
70	140	150	6	4	38.16	20.02	53.07

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Extruded %OIC	Pressed %OIC	Extraction efficiency (%)
71	140	90	7	5	28.18	15.36	63.99
72	120	120	7	4	33.50	17.36	59.31
73	100	150	7	3	32.51	14.03	67.11
74	120	90	6	3	27.18	14.03	67.11
75	120	90	7	5	20.85	12.20	71.40
76	120	150	6	4	33.50	16.19	62.04
77	120	120	6	4	32.51	16.69	60.87
78	100	90	5	5	22.02	11.87	72.18
79	80	90	7	5	20.02	9.70	77.26
80	80	90	5	4	25.18	10.70	74.92
81	120	120	5	3	35.83	16.36	61.65
82	120	90	5	3	30.34	15.19	64.38
83	120	90	6	5	22.02	11.70	72.58
84	140	150	7	4	36.17	19.86	53.46
85	100	90	7	5	19.69	11.53	72.97
86	140	120	7	3	36.67	18.86	55.80
87	80	150	5	4	23.52	11.03	74.14
88	80	150	5	3	32.17	12.37	71.01
89	140	150	7	5	34.67	17.53	58.92
90	140	120	6	3	35.17	17.53	58.92
91	140	120	5	5	33.34	15.69	63.21
92	100	150	5	5	23.68	9.87	76.87
93	100	120	7	5	27.51	12.20	71.40
94	140	150	6	3	38.50	19.69	53.85
95	140	90	5	4	30.67	17.53	58.92
96	120	120	6	5	24.68	12.70	70.23
97	120	150	6	3	36.17	14.53	65.94
98	140	150	7	3	36.33	17.69	58.53
99	140	120	6	5	29.34	14.86	65.16
100	120	150	5	4	32.84	15.36	63.99
101	100	120	7	3	30.51	12.70	70.23
102	120	120	7	5	26.18	13.53	68.28
103	120	150	7	5	28.51	13.36	68.67
104	140	120	5	3	37.00	18.52	56.58
105	80	120	5	3	26.68	10.37	75.70
106	100	150	5	3	32.34	12.70	70.23
107	100	150	6	4	28.68	12.86	69.84
108	140	90	6	5	24.68	14.20	66.72

Statistical Analysis

Analysis of Variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Temp	3	610.0168	203.3389	208.11	<0.001
speed	2	36.3845	18.1922	18.62	<0.001
die	2	8.6668	4.3334	4.44	0.023
CR	2	56.8146	28.4073	29.07	<0.001
temp.speed	6	8.9313	1.4885	1.52	0.213
temp.die	6	1.4608	0.2435	0.25	0.955
speed.die	4	4.0341	1.0085	1.03	0.411
temp.CR	6	21.2371	3.5395	3.62	0.011
speed.CR	4	2.0336	0.5084	0.52	0.722
die.CR	4	9.1515	2.2879	2.34	0.084
temp.speed.die	12	21.5451	1.7954	1.84	0.099
temp.speed.CR	12	6.8501	0.5708	0.58	0.833
temp.die.CR	12	9.9896	0.8325	0.85	0.601
speed.die.CR	8	6.0519	0.7565	0.77	0.629
Residual	24	23.4499	0.9771		
Total	107	826.6177			

Significant tables of means

Grand mean 13.992

Temperature	80	100	120	140
% OIC	11.404	12.415	14.535	17.613

Screw speed	90	120	150
% OIC	13.198	14.206	14.571

Die size	5	6	7
% OIC	13.637	14.008	14.330

Compression ratio	3:1	4:1	5:1
% OIC	13.198	14.206	14.571

Temperature	Compression ratio	3:1	4:1	5:1
80		11.368	11.551	11.292
100		13.162	12.587	11.496
120		15.398	15.196	13.012
140		18.156	18.619	16.064

Least significant differences of means

Table	Temperature	Screw speed	Die size	Compression ratio
replications	27	36	36	36
d.f.	24	24	24	24
l.s.d.	0.5552	0.4809	0.4809	0.4809

Table	Temperature Compression ratio
replications	9
d.f.	24
l.s.d.	0.9617

Stratum standard errors and coefficients of variation

d.f.	s.e.	cv%
24	0.9885	7.1

Appendix G

Results table and statistical analysis for laboratory 3 The effect extrusion variables have on the efficiency of the process as a preparation treatment. - Extruder power requirement

Results table - Extruder power requirement

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Power requirement (j/g)
1	80	150	7	5	
2	100	150	7	5	334.04
3	140	90	5	3	332.61
4	100	90	5	4	349.52
5	140	90	6	4	380.82
6	80	120	7	5	328.87
7	120	120	5	5	385.42
8	80	120	7	4	335.15
9	100	120	5	3	334.91
10	80	150	5	5	392.79
11	140	90	7	3	361.90
12	80	90	6	5	353.66
13	80	90	7	4	363.71
14	80	120	7	3	270.72
15	140	90	6	3	328.27
16	80	150	6	3	305.64
17	140	120	5	4	402.31
18	120	90	7	4	340.30
19	140	150	5	4	412.11
20	80	120	5	4	341.41
21	80	90	7	3	319.46
22	120	150	6	5	309.67
23	140	90	7	4	385.77
24	120	120	5	4	375.35
25	100	120	6	5	326.99
26	120	120	7	3	268.32
27	80	90	6	4	402.01
28	100	120	5	5	342.89
29	140	120	6	4	350.09
30	120	90	6	4	375.14

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Power requirement (j/g)
31	80	120	6	3	364.64
32	80	150	7	4	352.71
33	100	150	5	4	352.61
34	100	150	6	3	346.33
35	140	150	5	5	442.33
36	100	120	6	4	347.49
37	80	150	6	4	370.57
38	80	90	6	3	325.52
39	80	120	6	4	385.03
40	80	150	6	5	355.49
41	120	150	5	3	344.48
42	80	120	5	5	326.60
43	100	90	6	4	372.14
44	80	90	5	3	328.73
45	100	90	6	5	350.21
46	100	150	6	5	394.15
47	120	150	5	5	412.28
48	80	90	5	5	347.56
49	100	120	6	3	339.71
50	140	120	7	5	339.82
51	100	90	6	3	280.30
52	120	120	6	3	347.11
53	120	150	7	4	424.63
54	140	120	7	4	367.77
55	140	150	5	3	379.00
56	120	90	5	4	347.02
57	80	120	6	5	383.03
58	100	150	7	4	354.44
59	120	90	5	5	330.19
60	100	120	5	4	349.68
61	140	90	5	5	365.45
62	140	150	6	5	413.48
63	120	150	7	3	409.12
64	100	90	5	3	305.32
65	120	90	7	3	314.05
66	80	150	7	3	364.45
67	100	90	7	4	368.34
68	100	120	7	4	347.04
69	100	90	7	3	319.10
70	140	150	6	4	367.34

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Power requirement (j/g)
71	140	90	7	5	341.65
72	120	120	7	4	338.46
73	100	150	7	3	358.75
74	120	90	6	3	318.61
75	120	90	7	5	324.96
76	120	150	6	4	338.18
77	120	120	6	4	327.27
78	100	90	5	5	348.17
79	80	90	7	5	377.05
80	80	90	5	4	344.69
81	120	120	5	3	380.50
82	120	90	5	3	337.41
83	120	90	6	5	326.82
84	140	150	7	4	389.65
85	100	90	7	5	325.07
86	140	120	7	3	343.74
87	80	150	5	4	342.41
88	80	150	5	3	334.68
89	140	150	7	5	369.12
90	140	120	6	3	320.15
91	140	120	5	5	375.08
92	100	150	5	5	319.43
93	100	120	7	5	322.25
94	140	150	6	3	387.27
95	140	90	5	4	330.27
96	120	120	6	5	330.13
97	120	150	6	3	356.17
98	140	150	7	3	338.60
99	140	120	6	5	319.61
100	120	150	5	4	328.11
101	100	120	7	3	356.52
102	120	120	7	5	345.11
103	120	150	7	5	329.59
104	140	120	5	3	352.34
105	80	120	5	3	310.45
106	100	150	5	3	322.34
107	100	150	6	4	329.76
108	140	90	6	5	324.13

Statistical Analysis

Analysis of Variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Temp	3	7826.2	2608.7	5.10	0.007
speed	2	8747.0	4373.5	8.56	0.002
die	2	784.7	392.3	0.77	0.476
CR	2	11137.1	5568.5	10.89	<0.001
temp.speed	6	4729.3	788.2	1.54	0.209
temp.die	6	6705.4	1117.6	2.19	0.082
speed.die	4	4348.7	1087.2	2.13	0.110
temp.CR	6	2664.6	444.1	0.87	0.532
speed.CR	4	3615.5	903.9	1.77	0.170
die.CR	4	3206.2	801.5	1.57	0.216
temp.speed.die	12	15639.2	1303.3	2.55	0.026
temp.speed.CR	12	5591.6	466.0	0.91	0.551
temp.die.CR	12	6184.4	515.4	1.01	0.472
speed.die.CR	8	7076.2	884.5	1.73	0.145
Residual	23(1)	11757.2	511.2		
Total	106(1)	99649.3			

Significant tables of means

Grand mean 349.80

Temperature	80	100	120	140
% OIC	347.99	340.65	363.73	346.83

Screw speed	90	120	150
% OIC	342.94	343.94	362.51

Compression ratio	3:1	4:1	5:1
% OIC	336.31	360.81	352.27

Least significant differences of means

Table	Temperature	Screw speed	Compression ratio
replications	27	36	36
d.f.	23	23	24
l.s.d.	6.153	5.329	5.329

Stratum standard errors and coefficients of variation

d.f.	s.e.	cv%
23	22.609	6.5

Appendix H

Results table and statistical analysis for laboratory 3 The effect extrusion variables have on the efficiency of the process as a preparation treatment. - Extruder throughput

Results table - Extruder throughput

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Throughput (kg/h)
1	80	150	7	5	
2	100	150	7	5	10.66
3	140	90	5	3	8.69
4	100	90	5	4	9.42
5	140	90	6	4	6.86
6	80	120	7	5	10.10
7	120	120	5	5	8.03
8	80	120	7	4	10.47
9	100	120	5	3	9.20
10	80	150	5	5	8.28
11	140	90	7	3	7.85
12	80	90	6	5	8.61
13	80	90	7	4	7.72
14	80	120	7	3	9.08
15	140	90	6	3	8.24
16	80	150	6	3	10.01
17	140	120	5	4	8.04
18	120	90	7	4	7.99
19	140	150	5	4	8.53
20	80	120	5	4	9.66
21	80	90	7	3	8.53
22	120	150	6	5	11.03
23	140	90	7	4	7.31
24	120	120	5	4	8.58
25	100	120	6	5	9.65
26	120	120	7	3	10.17
27	80	90	6	4	7.93
28	100	120	5	5	9.16
29	140	120	6	4	9.50
30	120	90	6	4	7.87

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Throughput (kg/h)
31	80	120	6	3	8.57
32	80	150	7	4	9.76
33	100	150	5	4	10.50
34	100	150	6	3	10.20
35	140	150	5	5	8.39
36	100	120	6	4	9.34
37	80	150	6	4	8.79
38	80	90	6	3	9.06
39	80	120	6	4	8.32
40	80	150	6	5	9.35
41	120	150	5	3	10.36
42	80	120	5	5	9.57
43	100	90	6	4	7.73
44	80	90	5	3	8.92
45	100	90	6	5	7.45
46	100	150	6	5	8.01
47	120	150	5	5	7.98
48	80	90	5	5	8.00
49	100	120	6	3	7.97
50	140	120	7	5	9.15
51	100	90	6	3	9.16
52	120	120	6	3	8.72
53	120	150	7	4	8.42
54	140	120	7	4	8.91
55	140	150	5	3	9.65
56	120	90	5	4	8.82
57	80	120	6	5	8.25
58	100	150	7	4	9.86
59	120	90	5	5	8.78
60	100	120	5	4	9.30
61	140	90	5	5	8.23
62	140	150	6	5	8.63
63	120	150	7	3	8.45
64	100	90	5	3	9.28
65	120	90	7	3	9.12
66	80	150	7	3	8.96
67	100	90	7	4	7.85
68	100	120	7	4	9.21
69	100	90	7	3	9.03
70	140	150	6	4	10.17

contd.

Run Number	Barrel temp. (°C)	Screw speed (rev/min)	Die size (mm)	CR	Throughput (kg/h)
71	140	90	7	5	8.78
72	120	120	7	4	9.70
73	100	150	7	3	9.61
74	120	90	6	3	9.47
75	120	90	7	5	9.34
76	120	150	6	4	11.46
77	120	120	6	4	10.22
78	100	90	5	5	8.22
79	80	90	7	5	7.95
80	80	90	5	4	8.66
81	120	120	5	3	8.27
82	120	90	5	3	8.33
83	120	90	6	5	9.20
84	140	150	7	4	9.23
85	100	90	7	5	9.11
86	140	120	7	3	9.63
87	80	150	5	4	10.74
88	80	150	5	3	10.97
89	140	150	7	5	10.18
90	140	120	6	3	10.72
91	140	120	5	5	8.54
92	100	150	5	5	11.27
93	100	120	7	5	10.52
94	140	150	6	3	9.21
95	140	90	5	4	9.04
96	120	120	6	5	9.89
97	120	150	6	3	10.19
98	140	150	7	3	11.09
99	140	120	6	5	10.12
100	120	150	5	4	11.37
101	100	120	7	3	9.34
102	120	120	7	5	9.57
103	120	150	7	5	11.31
104	140	120	5	3	9.51
105	80	120	5	3	10.54
106	100	150	5	3	11.56
107	100	150	6	4	10.50
108	140	90	6	5	9.39

Statistical Analysis

Analysis of Variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Temp	3	2.3328	0.7776	1.42	0.262
speed	2	33.8713	16.9356	31.00	<0.001
die	2	0.2796	0.1398	0.26	0.776
CR	2	1.4108	0.7054	1.29	0.294
temp.speed	6	2.5817	0.4303	0.79	0.589
temp.die	6	9.9408	1.6568	3.03	0.025
speed.die	4	3.0122	0.7531	1.38	0.272
temp.CR	6	2.7391	0.4565	0.84	0.555
speed.CR	4	2.9193	0.7298	1.34	0.287
die.CR	4	8.9240	2.2310	4.08	0.012
temp.speed.die	12	12.1288	1.0107	1.85	0.099
temp.speed.CR	12	5.3531	0.4461	0.82	0.633
temp.die.CR	12	5.7415	0.4785	0.88	0.581
speed.die.CR	8	7.9763	0.9970	1.83	0.124
Residual	23(1)	12.5652	0.5463		
Total	106(1)	110.6207			

Significant tables of means

Grand mean 9.23

Screw speed	90	120	150
% OIC	8.50	9.32	9.86

Least significant differences of means

Table	Screw speed
replications	36
d.f.	23
l.s.d.	0.174

Stratum standard errors and coefficients of variation

d.f.	s.e.	cv%
23	0.739	8.0

Appendix I

Results table for laboratory experiment 4. Increased temperature range

Temperature (°C)	Extruded % OIC	mean	Pressed %OIC	mean
50	31.67		11.37	
50	30.84		10.53	
50	32.51	31.67	10.37	10.76
60	30.01		10.04	
60	28.34	29.18	10.20	10.12
70	15.36		9.87	
70	15.36	15.36	10.20	10.04
80	17.86		9.70	
80	15.69	16.78	10.70	10.20
100	22.02		11.87	
100	20.69	21.35	10.87	11.37
120	20.35		12.20	
120	24.52	22.43	12.37	12.28
140	25.51		14.36	
140	29.84	27.68	16.19	15.28

Extrusion conditions

Screw speed 90 rev/min
 Die size 5 mm
 Compression ratio 5:1

Appendix J

Results table and statistical analysis for large scale extrusion experiment 1 The effect extrusion variables have on the efficiency of the process as a preparation treatment. - Residual oil analysis

Results table - Residual oil analysis, Extruded

Temperature	% OIC			Mean	St Dev
	1	2	3		
0	40.83	40.99	37.66	39.83	1.88
40	25.51	28.01	27.68	27.07	1.36
80	36.00	33.84	30.67	33.50	2.68
120	38.00	36.67	34.84	36.50	1.59
150	36.50	39.66	42.16	39.44	2.84

Results table - Residual oil analysis, Single press

Treatment	% OIC			Mean	St Dev
	1	2	3		
0	13.03	13.86	14.03	13.64	0.54
40	12.53	12.86	12.53	12.64	0.19
80	12.86	15.69	13.53	14.03	1.48
120	16.36	13.86	14.20	14.81	1.36
150	13.03	14.53	13.03	13.53	0.87
Untreated	15.53	15.36	15.19	15.36	0.17
Cooked seed	16.19	16.53	16.19	16.30	0.20
Milled	12.86	16.36	15.03	14.75	1.77
Milled and cooked	12.37	11.2	13.7	12.42	1.25

Results table - Residual oil analysis, Double press

Treatment	% OIC			Mean	St Dev
	1	2	3		
0	10.53	11.20	10.70	10.81	0.35
40	11.70	11.37	11.20	11.42	0.25
80		12.70	12.37	12.54	0.23
120	13.36	13.53	12.86	13.25	0.35
150	13.03	12.03	12.20	12.42	0.54
Untreated	12.86	12.53	12.53	12.64	0.19
Cooked seed	12.86	13.03	12.7	12.86	0.17
Milled		13.2	12.03	12.62	0.83

Statistical Analysis*Analysis of variance*

Source	DF	SS	MS	F	P
Treatment	8	38.43	4.80	4.39	0.004
Error	18	19.70	1.09		
Total	26	58.14			