# PLASTIC FILM RECYCLING FROM WASTE SOURCES

A Thesis submitted to the University of Wales for the Degree of

**Doctor of Philosophy**

By

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# Declaration

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Signed R. Marsh (Richard Marsh)

Date 11/03/2005

Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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# Summary

This thesis focuses on the thermal recycling of plastic film materials that have originated from waste sources. The problems with waste plastic film recycling are outlined. The key aspects of this work included waste management, economics, logistics, the recycling industry, aspects of polymer science and the effect of the consumer environment on material properties of polymers. The aim of the research was to determine how these problems can be best understood and solved in order to prove that plastic film recycling is a sound opportunity from a financial and engineering point of view.

A series of novel experimental studies were designed and performed to evaluate the effect that a film's life-cycle has on the material properties of the product. These studies involved exposing a number of polyethylene samples to factors such as heat cycling and dust contamination whilst measuring the characteristics of the material before and after exposure. Material tests included evaluation of mechanical and rheological properties, crystallinity content and molecular weight.

As a natural continuation of the behaviour and characteristic studies already highlighted, two novel products namely a geomembrane and aggregate drainage material were manufactured. Tests were undertaken to determine the suitability of these under harsh environmental conditions. It was found that both materials were capable of meeting specifications laid down for application as engineering barriers.

With the effects of a products' life-cycle understood, the investigation then involved the development of a predictive model. This anticipated the effects of these life-cycle factors and calculated the resultant physical properties of a plastic film material once it had been thermally recycled. This model used correlations between the key factor and the crystallinity of the polymer in order to determine the degradative effects. Results showed that key material properties could be modelled to within 15% accuracy of those found by experimental verification.

To assess the feasibility of recycling plastic film an economic model was produced to simulate the financial performance of a recycling plant. Model inputs were based on industrial experiences and were used in conjunction with a series of operating parameters to outline economic feasibility. The simulation showed that profitability was closely related to the quality of the input material, the cost of procuring waste feedstocks and the price paid for the final product.

Overall the thesis showed that plastic film recycling is a viable concept, provided recyclers sufficiently improve the quality of feedstocks by separation and washing, procure a reliable source of feedstock and operate a facility that is adaptable to changes in material condition. These factors must be undertaken with sound financial management to ensure that a profitable product is produced.

Although there is a small number of possible recycled products to be produced from plastic film, more development is needed to create a demand for waste feedstock materials. This will ensure that mandatory recycling targets are met for government and businesses that are required by European legislation. This investigation has outlined many of the key factors to allow film recycling businesses to expand into future markets and produce recycled products of equal quality to that of existing products made from virgin stocks.

# Acknowledgements

I would like to express my thanks to all of my colleagues that have encouraged and assisted me with this investigation.

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# Contents

# Nomenclature

| Symbol | Definition | Units |
|---|---|---|
| k | Hydraulic conductivity | m/sec |
| Mn | Molecular Weight (based on number) | atomic mass units |
| Mw | Molecular Weight (based on mass) | atomic mass units |
| $m$ | Average mass of cut-offs | g |
| $m_{nom}$ | Nominal load | kg |
| n | Squares of molecular weights in sample | - |
| N | Square of number of samples | - |
| q | Dimensionless radiative intensity | - |
| R | Correlation coefficient | - |
| $t$ | Cut-off time interval | Minutes |
| $t_{ref}$ | Reference time | Minutes |
| $w_x$ | Molecular weights in sample | atomic mass units |
| w | Number of samples | - |
| x | Number average of molecular weight | atomic mass units |
| $x_w$ | Weight average of molecular weight | atomic mass units |
| $\lambda$ | Wavelength of X-Ray radiation | metres |
| $\theta$ | X-Ray scattering angle | degrees |
| $\theta_t$ | Test temperature | °C |

# List of abbreviations

%El - Percentage Elongation
ABS - Acrylonitrile-Butadiene-Styrene
APD - Automated Powder Diffractometer
ASCII - American Standard Code (II)
ASR - Automatic Scrap Recycling
BOD - Biological Oxygen Demand
BPEO - Best Practicable Environmental Option
BS - British Standard
CA - Civic Amenity
COD - Chemical Oxygen Demand
DEFRA - Department of the Environment, Food and Rural Affairs
DETR - Department of the Environment, Transportation and the Regions
EA - Environment Agency
EU - European Union
GPC - Gel Permeation Chromatography
HDPE - High Density Polyethylene
KAG - Continuous Agglomerator
LDPE - Low Density Polyethylene
LLDPE - Linear Low Density Polyethylene
MBT - Mechanical Biological Treatment
MFI - Melt Flow Index
MRF - Materials Recovery Facility
MSW - Municipal Solid Waste
MWD - Molecular Weight Distribution
NAW - National Assembly for Wales
PAS - Publicly Available Specification
PC - Polycarbonate
PC - Personal Computer
PE - Polyethylene
PERN - Packaging Export Recovery Note
PET - Polyethylene Tetraphthalate
PI - Polydispersity Index

| | | |
|---|---|---|
| PID | - | Proportional, Integral, Differential |
| PP | - | Polypropylene |
| PRN | - | Packaging Recovery Note |
| PS | - | Polystyrene |
| PVC | - | Polyvinyl Chloride |
| RPL | - | Recycled Plastic Lumber |
| SEC | - | Size Exclusion Chromatography |
| TCB | - | Trichlorobenzene |
| TOC | - | Total Organic Carbon |
| UTS | - | Ultimate Tensile Strength |
| UV | - | Ultra Violet |
| WRAP | - | Waste Resources Action Program |
| WTO | - | World Trade Organisation |
| XRD | - | X-Ray Diffraction |

# Chapter 1 – Introduction

## 1.1 Background

There are a number of problems and barriers that restrict the amount of plastic film recycling that can currently be realistically performed in the UK. For this reason landfilling of plastic film waste is still the most popular disposal route. Stringent targets for diversion and recycling of household, commercial and industrial wastes mean that recycling processes and the application of recycled material need to be more fully understood. Many of the barriers to achieve such recycling targets arise from difficulties in material procurement, manufacture, marketability of new products and overall economics.

Taken in a modern context there are generally two reasons for undertaking any recycling activity. The first reason is that of economics, i.e. to reduce process losses or to make a profit by producing material from a waste (rather than using a so-called 'virgin') source. The second reason is that of environmental or political pressure, which is concerned with recycling excess material in order to reduce waste materials that would normally be put into a disposal facility, which reduces the environmental impact.

In the context of plastic film recycling the main purpose is that of economics. As later sections will show, plastic film is a fairly small constituent of solid waste in the UK by mass, but the economic returns from its recycling are substantial to support a multi-million pound industry. However, there is always political pressure from lobbyists to support recycling as plastic is non-biodegradable and therefore will not decompose over time. This implies that although economics are the principal reasons, there is still support for plastics recycling from an ecological point of view.

Plastic film applications (principally in packaging) have seen huge growth in the previous 30 years. This is mostly because of enhancements in manufacturing technology and reductions in material costs, due to imports from developing countries. This increase has meant that plastic film has become an increasingly larger constituent of municipal wastes, triggering environmental concerns from environmental bodies and government departments. Comparatively speaking plastic film recycling is more difficult than the recycling of other materials, such as metals or glass because of process problems, difficulties in removing contaminants and the harsh economics involved in running a film recycling operation. For these reasons the plastic film recycling industry has been largely unable to recover value from material that has arisen from municipal sources.

Plastic is a very popular material in modern packaging applications for five main reasons:

- Low-cost of production and manufacture.
- Chemical inertness.
- Excellent strength-to-weight ratio.
- Ability to have a range of gas and liquid permeablities.
- Ability to be formed into thin films that are easily wrapped around goods.

For packaging there are three major sub-classes, primary, secondary and tertiary. Primary packaging is a term given to material that is in direct contact with the packaged product (for example a milk bottle). Secondary packaging is material that is used to agglomerate packaged goods into packs (for example shrink-wrap or multi-pack cartons). Tertiary packaging is the name given to material that is used to ship packaged goods (for example pallets or pallet wrapping) [1].

The plastic film recycling industry cites contamination in the form of non-compatible plastics, non-plastics and food residue as the main barrier to further recycling [2 3, 4]. Understanding the fundamentals of polymer chemistry is vital when solving problems arising from the physical process of plastic degradation during recovery and recycling.

Polymer degradation during recycling is an engineering subject that has received little attention. This is mainly due to the small scale at which plastic recycling is presently conducted. Future legislation indicates that plastic recycling will become more frequent and therefore it is assumed that the understanding of the effect of recycling on plastic materials will be more significant. Without a saleable and profitable product, recycling markets often fail, which is why it is important to understand the physical properties of a reprocessed product before undertaking its recycling on an industrial level.

Developing a method of predicting the resultant properties of a recycled product before the recycling process (and its inherent expense) has been undertaken would be a powerful tool to a recycler. This can be undertaken by factoring certain degrading effects, such as heat-cycling or dust contamination, to quantitatively predict the change in strength or viscosity of the reprocessed mixture. Such a tool would inform recyclers as to the quality of their output before manufacture, such that they might be able to calculate if the final product would a.) meet material specifications and b.) be profitable when sold in an open market.

Data from a 2000 government survey by the Department of Environment, Transport and the Regions (DETR) [5, 6] and census data [7], is a reliable indicator as to the total amount of waste in the UK. Figure 1.1 gives details of the amounts of waste produced in the UK, depending on whether it came from industry, commerce or the home. Uncontrolled wastes (wastes not subject to regulation by the Environment Agency) are shown as red bars and controlled wastes (wastes which are subject to such regulation) are shown as blue bars. It can be seen that industry produces far more waste than households. However, industrial and commercial waste streams are far more specialised in their nature and as such are generally source segregated prior to disposal.

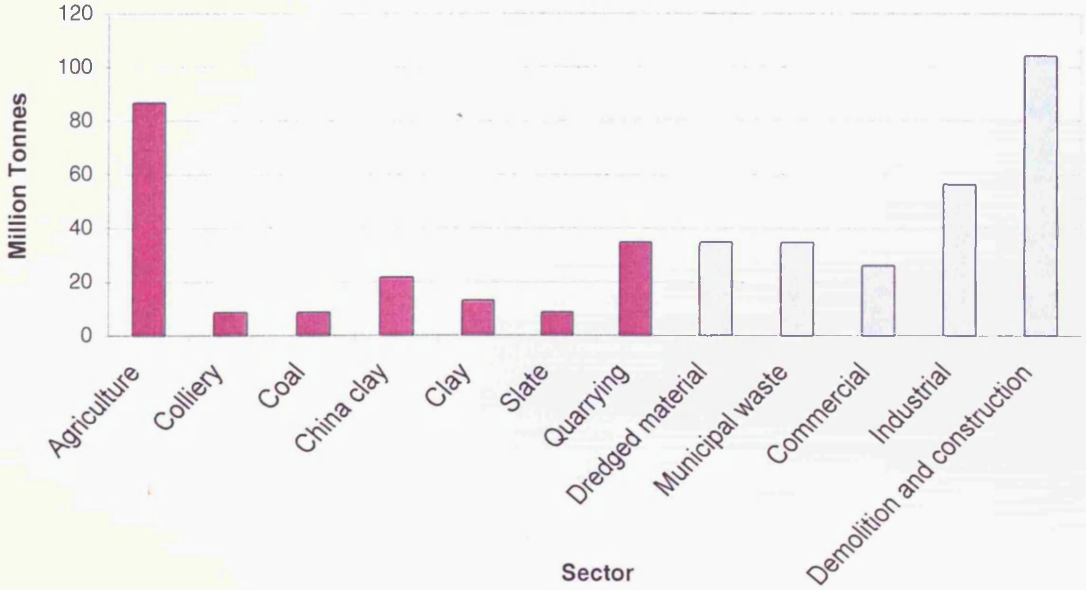


Figure 1.1 Waste production in England and Wales 1998 / 1999 [5].

The amount of plastic sheet in the UK domestic waste stream is about 4% by mass. Municipal waste production is currently of the order of 30 million tonnes per annum, with about 25 million from households, thus it can be assumed that municipal sources produce around 1.2 million tonnes of plastic film per year [8], see also Appendix A for a classification of the constituents of municipal waste. Trends in the usage of plastics in packing imply that this figure will increase, coupled with increases in production of MSW. Only a small proportion of this film is currently worth recovering for the purpose of recycling. Estimated amounts of plastic film in the Commercial and Industrial sectors are of the order of 1 million tones per annum [9]. Therefore in total the UK produces an average of around 2.5 million tonnes of plastic film per annum. According to industry surveys it is understood that only 200,000 tonnes of this total was recycled [10, 11].

The use of plastics (both rigid and film) has increased steadily in the UK over the last 50 years, and is now about 5 million tonnes per annum. Of this, 1.6 million tonnes is used by the UK plastics packaging industry [12]. The breakdown of use by different sectors is shown in Figure 1.2, where the legend is in descending order of magnitude of use. Packaging is the primary use for plastic in the UK, followed by the building applications and electrical sectors. In terms of plastic waste, packaging made up about 36% and about half of this amount (54%) was used for food applications. About three-quarters of plastic packaging ends up in the household waste stream, the remainder being secondary and tertiary distribution packaging (crates, pallets, wrapping, etc) in commerce and industry. In terms of recycling, of this annual total, approximately 500,000 tonnes (10%) was recycled in 2000, this included 203,000 of plastic packaging recovered under the Packaging Waste Regulations [13, 14].

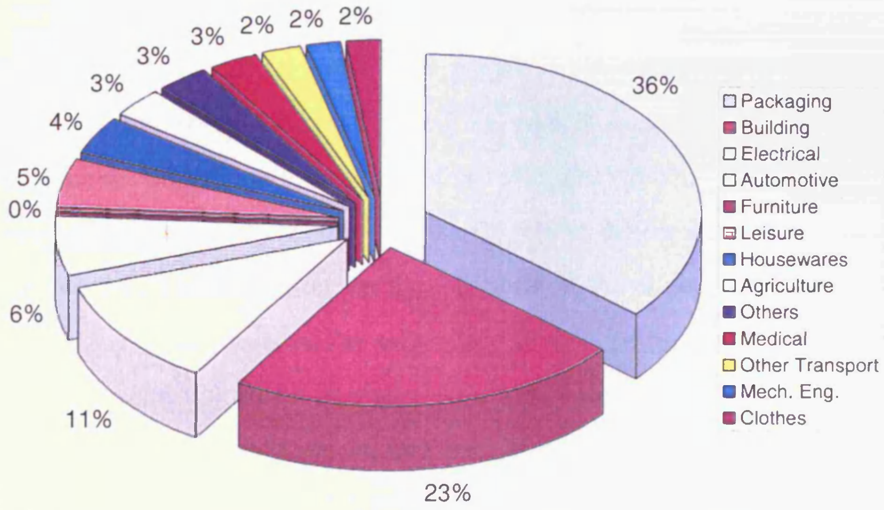


Figure 1.2 UK plastics applications, both rigid and film [12]

## 1.2 Sustainable waste management

The concept of sustainable waste management is intended to minimise the environmental impact of waste. Options such as landfill and incineration are well known as final treatments. This can also be referred to as 'linear waste management' because the material moves along a process from beginning to end with no element of re-use or re-circulation. Recycling can be referred to as 'circular waste management' because the material is re-integrated into product life-cycles a number of times before final disposal. Although recycling does not normally occur indefinitely (for example, the shortening of fibres in newsprint recycling), the recycling can occur more than once. This implies that such a waste option will conserve a certain amount of prime material and energy.

The legislative hierarchy, as far as how waste targets are set, begins with the European Commission who set the European directives. Member states (such as the UK) decide on their own national legislation to meet the targets within their own countries. As far as the Welsh strategy is concerned, the National Assembly of Wales decides whether the national target meets their ideals or if it should be changed. The Assembly then publishes a waste strategy with Welsh targets and local governments decide on how they will meet these targets, as shown in Section 1.2.2.

In terms of plastics, the matter of whether it is more ecologically sound to incinerate plastics rather than recycle them is still an unresolved issue [15]. The supporters of incineration say that segregating, collecting, transporting and recycling plastics uses more energy than the energy liberated when combusting the plastic as fuel. On the other hand, energy recovery from waste plastics is potentially unsound from an environmental point of view. The possibility of generating toxic gases, in particular chlorine-containing dioxins, from PVC makes incineration unpopular. Pressure from the public could lead to legislation changes in the future that would end such practices. This could result in plastic waste being treated (for example sorted to remove PVC) before entering the incinerator. Parallels can be made between this and the segregation stage when recycling plastic films, which implies that all plastic disposal technologies of the future could require a manual sorting stage.

It has been argued that recovering energy from waste plastic is environmentally more beneficial than the recycling process [16]. Dioxin production from the incineration of mixed plastic has raised concerns over this disposal method.

### 1.2.1 Packaging legislation – industrial and commercial waste sources.

The recovery of packaging from industrial and commercial sources for recycling was made a legal obligation in 1997. Legislation was brought in via Statutory Instrument 1997 No. 648 - The Producer Responsibility Obligations (Packaging Waste)

Regulations 1997 [13]. The UK is required to recover and recycle a minimum amount of packaging, as shown in Table 1.1.

Table 1.1 Packaging recovery and recycling targets

| Year | Amount of industrial waste to be recovered | Amount of industrial waste to be recycled |
|---|---|---|
| 1998 | 38% | 7% |
| 1999 | 43% | 10% |
| 2000 | 45% | 13% |
| 2001 | 56% | 18% |
| 2002 | 59% | 19% |

The packaging regulations apply equally in England, Wales, Scotland and Northern Ireland to all obliged businesses involved in the packaging chain. Obligated businesses handle more than 50 tonnes of packaging material in a year and have an annual turnover of at least £2 million. Businesses that have packaging arisings or turnovers less than the prescribed limits are considered exempt. Businesses affected by the Regulations must either join a registered compliance scheme or register with the Environment Agency as an individual business. The UK recycled over 4.8 million tonnes of packing waste in 2002 as a result of regulations enforced by the Environment Agency.

The legislation prescribes that recyclable material is classed as:

- Glass
- Aluminium
- Steel
- Paper / fibreboard
- Plastic
- Packaging material composed of a combination of any of those materials (treated as made of the material which is predominant by weight.)

Since the establishment of these regulations, the Environment Agency has prosecuted a number of companies that have failed to show appropriate returns to prove that their obligations have been met [17].

Returns, i.e. paperwork that defines the amount of packaging that has been recycled is in a format known as a Packaging Recovery Note (PRN). These notes are issued by accredited recycling operations to either the waste producer or the broker running the compliance scheme that the producer is attached to. PRNs can also be traded, and their prices are set by the accredited recyclers, these prices can often change, dependent of economic factors. As an example of typical values, Table 1.2 shows the variation in PRNs in June and July 2004, historical set of data is shown in Appendix B.

Table 1.2 PRN values for June and July 2004.

| Material | Price June 2004 (£ / tonne) | Price July 2004 (£ / tonne) |
|---|---|---|
| Glass | 23 – 27 | 22 - 27 |
| Paper | 9 - 10 | 9 - 10 |
| Aluminium | 21 – 26 | 23 - 28 |
| Steel | 12 – 16 | 14 - 16 |
| Plastics | 8 – 10 | 8 - 10 |
| Mixed — energy recovery | 2 – 4 | 2 - 4 |
| Wood | 8 – 10 | 8 - 10 |

Comparing these values to that of the price paid for recyclates, it is apparent that PRNs generate less income for the waste producer than simply selling waste for cash. This is so that the economics of a recycling plant will be favoured as they will be paying less for waste if they issue PRNs. The net effect of this is therefore twofold:

1. Obliged companies can meet the packaging regulations targets.
2. Recyclers will operate more profitably if they issue PRNs rather than pay cash.

A 2004 investigation carried out by DEFRA, concluded that false reporting and fraud had been evident by the reprocessors, potentially over-estimating by as much as 34,000 tonnes [18]. The investigation showed that reprocessors and exporters have been incorrectly issuing compliance documentation (PRNs) and Packaging Waste Export Recovery Notes (PERNs) - during 2002 and 2003 which made it appear that they were recycling more plastic packaging waste in reality. In a limited number of cases the police were notified.

Waste arising from municipal sources is not subject to packaging legislation. It is likely, however, to be legislated via household waste recycling targets, as mentioned in Section 1.2.2. There are no guidelines as to the specific material that must be recycled from household waste sources, which can potentially be detrimental to smaller streams, such as packaging film, because of the greater abundance of streams such as garden waste.

### 1.2.2 Municipal solid waste recycling

UK targets for the recycling of Municipal Solid Waste (MSW) were implemented via waste strategy targets, from the Landfill directive [5]. Welsh targets for the recycling and composting of MSW [19] are:

- By 2003/04 achieve at least 15% recycling / composting of municipal waste with a minimum of 5% composting and 5% recycling.
- By 2006/07 achieve at least 25% recycling / composting of municipal waste with a minimum of 10% composting and 10% recycling.
- By 2009/10 and beyond achieve at least 40% recycling / composting of municipal waste with a minimum of 15% composting and 15% recycling.

In terms of Welsh performance, the proportion of municipal waste being recycled or composted increased from 8.4% in 2001-02 to 12.6% in 2002-03. These statistics show that Wales must increase its municipal recycling rate by a further 2.4% in 2003-04 if is to reach the 15% target.

Waste from household sources only in Wales (1.49 million tonnes) accounted for 83% of municipal waste in 2002-03. 12% of household waste was collected for recycling or composting in 2002-03, up from 8.7 per cent in 2001-02 [20].

In terms of how this material travels from the source to the point of disposal, treatment or recycling facility, it is useful to introduce the concept of a 'waste chain'. Figure 1.3 shows a typical waste chain, where the waste material is handled by a transporter and either bulked or separated at a Materials Recovery Facility (MRF). After separation and bulking, the material will be shipped to a recycler for processing into a new product. Controlled wastes are subject to Environment Agency regulation for storage, transport and disposal, as shown in Figure 1.3.

Companies that transport waste must be registered with the Environment Agency and companies that process or dispose of waste (including recyclers) must have a licence or permit from the Environment Agency. Some companies can be exempt from licensing and permitting, but they must be inspected beforehand and issued with an exemption certificate. This shows that running a recycling operation requires an appreciation for legislation.

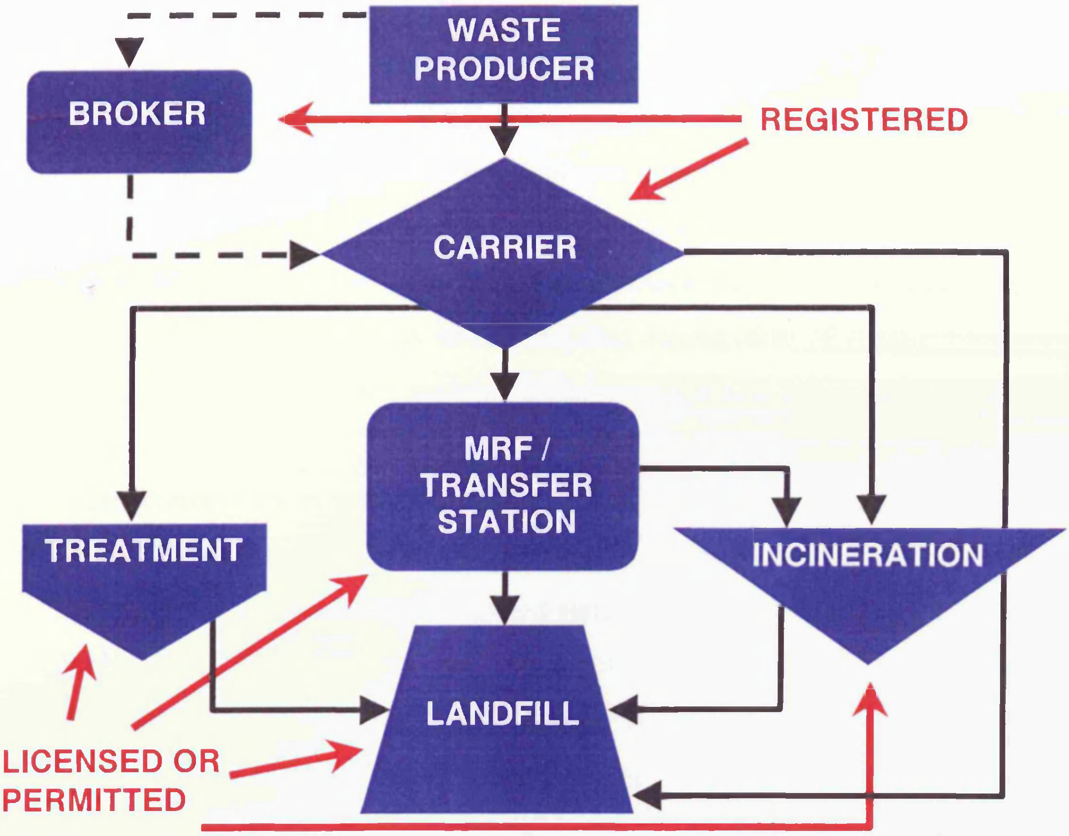


Figure 1.3 A waste chain [21]

## 1.3 Plastic film applications and recycling

Searches of UK businesses associated with plastic film reprocessing have been previously studied [4, 22]. It was found that between 60 and 80 firms were listed as trading in the industry of recycling plastic sheet, be it collection and/or recycling. The industry itself is not straightforward - some businesses take in plastic sheet, separate, wash and granulate, and then finally melt and extrude it into new products. Other companies only process the sheet up to the point of granulation, then sell the granulated material to an end product manufacturer. The state of the industry is very fluid, depending on issues such as income and market prices. Some firms believed that plastic sheet reprocessing should only be done as an aside to the reprocessing of rigid plastic, due to the poor prices paid for recycled plastic sheet. A list of the firms currently engaged in collection and recycling is given in Appendix C.

Much of the activities in modern plastic film recycling are based on recovery of scrap or off-cut material at manufacturing sites. This is undertaken for economics, such that value can be gleaned from manufacturing scrap, rather than wasting what is essentially usable material. The recycling market for back-of-store packaging film, material which has not yet passed into the consumer domain is steadily growing, but film recycling from post-consumer sources is virtually non-existent. As with the recovery of any waste material the net economics of the whole process, from initial consumer disposal, through the recovery and recycling phases, to re-marketing as a new consumer product, must be favourable or the recovery operation will not function economically. Plastic film is an extremely voluminous material per unit mass. Its bulk density will form an integral part in arguing that segregation of plastic film waste from other non-bulky materials, such as paper waste, could bring savings in waste disposal costs.

Plastic film recovery from post-production sources in the UK is currently run by a number of well-established businesses. These firms generally have contracts arranged with film producers to recycle their aborted runs, end of lines and other blown film that failed to make it to the consumer. Searches of UK businesses associated with plastic film reprocessing showed that at least 86 firms were listed as trading in the industry of recycling plastic film. Overall their production rate is less than 10% of total UK plastic film production [23].

The industry for recovering waste plastic film post-consumer is still in its infancy. This is attributed to there being few immediate benefits to recycling this material, in comparison to the work required to collect the film and get it to a high enough standard before reprocessing. Prospects for the future appear to point towards increased recycling in all material sectors and increases in waste disposal costs, according to the DETR [5]. Drivers for these changes have come from government targets, handed down through European Legislation [24]. If such legislation is fully implemented, waste disposal via recycling may become artificially cheaper than using landfill in the future due to added premiums on waste disposal, such as landfill tax.

Generally speaking, recycling of plastic film is only performed postproduction using production scrap such as aborted runs and roll-ends. Recycling of plastic film from municipal waste sources is not usually undertaken due to a number of technical barriers. The sources of plastic film dictate their recyclability and their likely composition. Data from Re-sourcing Associates [25], along with observations made in the UK recycling market are shown in

Table 1.3. Seven major sources of plastic film waste are illustrated, along with the types of plastic waste they include. Co-mingled household waste has not been

included as removal of contamination and segregation has previously proved too costly if the film is mixed with refuse.

Table 1.3 The three main sources of waste plastic film [25].

| Sector | Source within sector | Type of plastic waste |
|---|---|---|
| Post- industrial | Manufacturing scrap | Includes residues generated during primary production, such as edge trimmings or aborted batches. |
| | Re-manufacturing scrap | Includes residues generated during secondary processes, such as roll-ends or misprints. |
| Post-commercial | Commercial businesses | Shipping and receiving departments. Mostly packaging. |
| | Warehouse and distribution centres | Mostly packaging. Quality depends on type of business and goods that are stored by the business. |
| | Wholesalers | Used shipping packaging. Type and quality depends on nature of business and products supplied. |
| Post-consumer (municipal) | Distributor bring-back banks (at stores) | Located at supermarkets / civic amenity (CA) sites. More economical as certain types (e.g. grocery bags) can be targeted. |
| | Kerbside | Usually MRF sorted. Contamination the biggest problem. Problems with sorting of mixed film. |

The end products from recycling are dependent on the quality of the input feedstock. Thin film is the most profitable form of plastic film as it commands a higher price per tonne, but the input must be of very high quality prior to blowing. Thick film applications, which are the most common, include thicker refuse sacks, builder's sheets and damp-proof membranes. Sheet material is used in construction applications such as walkways and conduit covers. Recycled plastic lumber (RPL) is also used in construction applications such as fence-posts and garden furniture and is produced from poor-quality reclaimed plastic; both film and rigid resins are used.

Making a comparison with the paper recycling industry, a film recovery operation would benefit from an input material standard in order to determine the recyclability of the material and possible applications once recycled. The European paper industry uses EN643, which defines grades and combinations of the types of recovered papers that are acceptable for recycling, as shown in Appendix D. At the moment, educated guesswork by experts within the film recycling plants are used to judge whether the input material is suitable for recycling at the particular facility.

At time of writing a standard is being introduced, known as PAS 103, for the description of plastic waste material. This has been introduced to give some quantitative identification to the composition of plastic waste for recycling. Forms contain details of plastic composition, contaminant type and origins of the waste. This standard appears to be the start of quantifying an industry that has traditionally been run on the instincts of process operatives, rather than following a written procedure on the acceptance criteria of material at recycling plants. A copy of the PAS103 standard can be found in Appendix E.

### 1.3.1 Technical barriers to recycling

Two of the major obstacles with plastic film recycling are contamination and separation of polymer types. One of the most significant costs typically associated with recovery of plastic film is the labour time required to sort and handle the film. Washing technologies have improved the ability to remove a broad spectrum of contamination, but still represent one of the most expensive steps in processing films. Contamination is generally from bio-organic material, such as that used in food packaging, paper material from labels and thermoset polymers from adhesive packaging tapes. Developments in melt-filtering technology have meant that higher levels of contamination could be considered in film recycling, but research has not yet been conducted on how much is realistically acceptable. Recyclers and manufacturers must address issues such as resin variations and contamination levels within recovered plastic film streams. Hence recycling plastic film to produce more film is almost exclusively undertaken using material that has not been used by consumers.

There are a number of polymers used to make packaging film and their appearance can be fairly similar. Some film producers are labelling film products with standard resin codes, such as those seen on the underside of rigid products such as HDPE milk bottles [26], however, many applications do not warrant or permit resin code labelling. With appropriate expertise plastic films can be separated by visual identification. This may involve examining the texture of the films by hand to identify its resin. However, when using such techniques it is difficult to produce recyclates containing contaminant concentration of less than one part in one thousand, which is the quality required for some polymers. Density separation is also possible, simple techniques can separate polyethylene and polypropylene resins from other packaging plastics, although composite films may be incorrectly classified.

## 1.4 Economics

The economics of plastic film recycling is a key parameter in deciding feasibility. Prices for all recycled materials tend to fluctuate on a monthly basis. Fluctuations can depend on a number of local and global economic factors, much in the same way as public limited company stock prices or commodities can fluctuate on open markets. It is essential that all parties involved in recycling maintain an accurate materials price index if their operation is to run profitably. Figure 1.4 shows the value of waste rigid plastic from October 2000 to July 2004. Also shown on the graph is the value of Brent crude oil for the same period.

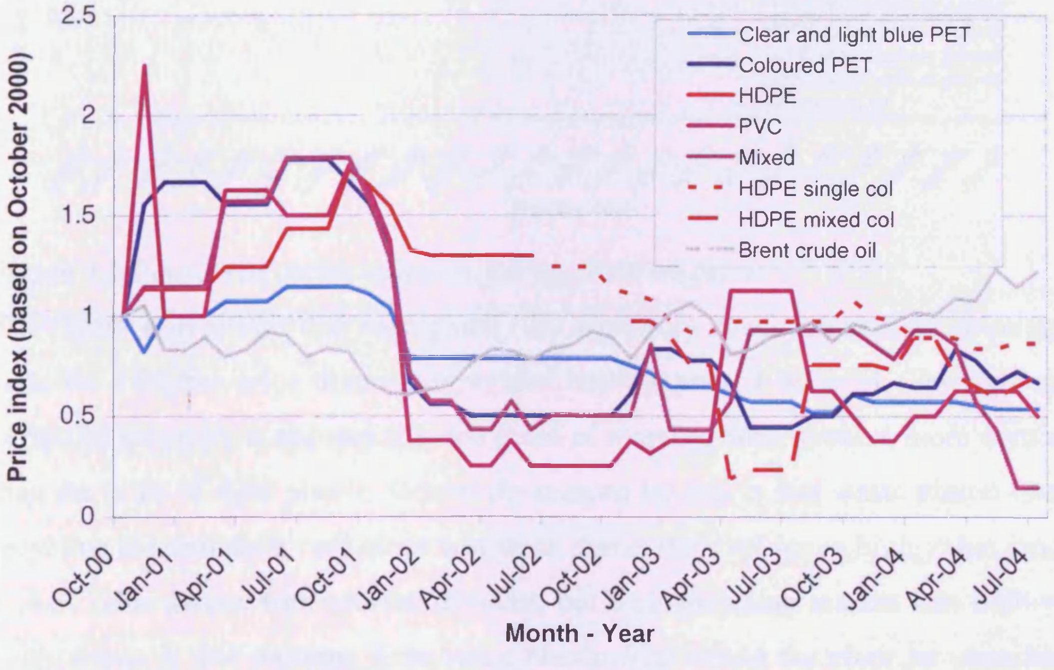


Figure 1.4 Rigid plastic price index including crude oil price [23].

The figure shows that there is perhaps a slight relationship between the price of oil and the price of recycled plastics, seen in the downturn around September 2001, but this is more likely due to the global effects of the September 11 terrorist attacks. From the start of 2002 to July 2004, the oil price has increased and plastic prices have fallen steadily, indicating that oil price does not affect the price of recycled plastics directly. The data also shows that source separated plastics normally sell at a higher price than that of mixed plastics, but can occasionally reduce to values similar to that of mixed plastics.

Figure 1.5 shows the price history of waste plastic film, including the Brent crude price. Although the film appears to hold a better relationship with the price of oil, the correlation between the two is still weak, indicating that there are many other factors that decide the value of waste plastic film.

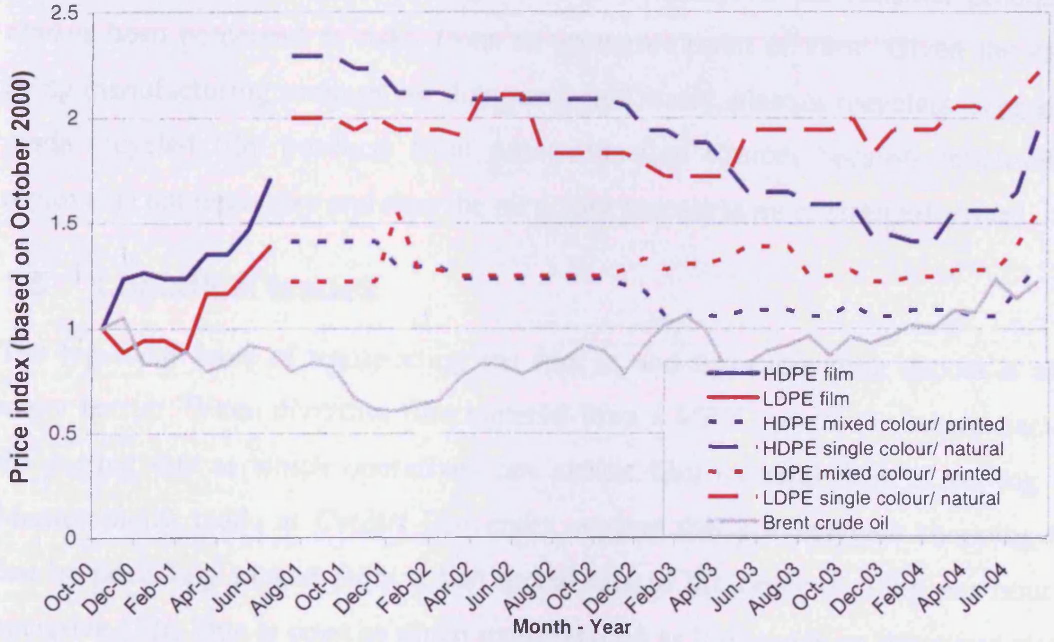


Figure 1.5 Plastic film price index including crude oil price.

The figure also shows that segregated film with only small amounts of printing ink sells for a higher price than unsegregated heavily printed material. Throughout the period in question, it appears that the price of recycled film remains more consistent than the price of rigid plastic. One of the reasons for this is that waste plastic film for recycling is normally a very clean feedstock that is recycled into a high-value product. Lower value plastic film sources do exist, but their recycling market into high-value applications is non existent. Low value plastic film would therefore be classified as "mixed plastic", and have a selling price of the material shown in Figure 1.4.

In terms of the whole recycling operation, including the waste chain, plastic film recovery and recycling requires overcoming the following obstacles: cost-effective diversion and collection from waste sources, the ability to sort similar materials into individual streams and the ability to remove contaminants from the stream.

Sorting materials into streams is especially difficult when dealing with plastic film as there is currently limited technology to perform the task automatically. The majority of plastic film in the waste stream is derived from polyethylene, namely High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Linear Low Density Polyethylene (LLDPE), and other plastics such as Polypropylene (PP), Polyvinyl Chloride (PVC) and Nylon. Identifying these materials in a cost-effective manner is difficult due to the similarities in their appearance and can often prove too difficult in a MRF-type operation. Removal of contamination is undertaken in a washing plant. The washing technology, with regard to profitability of the finished product has always been perceived as risky from an economic point of view. Given the ease of using manufacturing scrap rather than recovered waste, plastics recyclers have always made recycled film products from post-production sources because contamination removal is not necessary and thus the recycling process is more straightforward.

## 1.5 Logistical issues

The logistical issue of transporting the film to and from recycling depots is also a major barrier. When diverting film material from a MRF source, the critical factor is the sorting rate at which operatives can extract film material from a moving belt. Measurements made at Cardiff University suggest that polyethylene shopping bags can be positively picked from a belt at the rate of the order of 10kg per hour per operative [22]. This is open to much interpretation as it depends on the waste stream, technology used in the MRF and the type of plastic film that is being extracted. Given that total labour costs for a single operative in the UK would be of the order of £10 per hour, plastic film separation by hand would cost around £1,000 per tonne. Although this estimation is open to interpretation, it clearly illustrates that hand sorting of a material as bulky as plastic film is far from cost-effective. For this reason some waste management organisations are currently sending plastic film to be sorted in countries where labour costs are lower. Between November 2000 and November 2001, the UK collected an estimated 14,000 tonnes of plastic bottles, but 6,250 tonnes were exported overseas for recycling [27]. As mentioned earlier, separation accounts for most of the technical and financial challenges faced by the plastic film recovery industry.

Another major problem is that of bulk density. Plastic film material can be compacted and baled fairly easily with the correct equipment, but this may not always be the most effective treatment. Compaction reduces the specific volume of the material (i.e. lowers bulk density) but it can also induce contamination problems. Compaction squeezes the material closer together, mixing non-compatible plastics as well as agglomerating other contaminants. However, the economic saving made from compaction usually makes it critical for efficient recycling plant operation. This can lead to a situation where the point along the recovery route at which the material is compacted become crucial. Essentially a trade-off exists between the short-term economics of compaction and the process problems caused by addition of contamination.

It is possible that the variety of materials available for collection may change in the future. The proposed taxation on plastic bags [28] could have an effect on the film market. However this will not affect the supply of packaging film from the businesses themselves as only bags are currently proposed to be subject to taxation. Plastic film is not a major component of the UK waste stream, although it could account for up to 2.5 million tonnes of material sent to landfill per year. Overall, for both rigid and film plastics, the UK is poor at recycling with a rate of only 10% of the plastics waste produced [12]. The potential to increase plastic recycling rates is large and waste film recovery can make a significant contribution.

Ideally, a scheme similar to that of EN 643, which outlines the specification of waste paper and gives guidelines as to what can be accepted into paper mills, could be used to define waste plastic films. The specification could outline contamination levels, material type and allowable mixtures of different polymers. The acceptance of a standard by plastic film recyclers would help to clarify whether input batches delivered to a facility are acceptable for recycling. Should plastic film recycling from waste sources become more popular, waste managers will need to implement suitable collection strategies that take into account the problems discussed, namely bulk density issues, contamination and film separation.

## 1.6 Aims and structure of the thesis

The principal aims of this thesis are:

- To investigate the sources and quantities of plastic film that are fit for recycling present in the UK waste stream.

- To determine the feasibility of building an economically and scientifically sound methodology for the recycling of plastic film products that have arisen from waste sources.
- To evaluate the diminishing effect on the material properties of plastic film products made by the environmental factors encountered in a typical products' life-cycle.
- To produce a computational model that can anticipate these diminishing environmental effects, based on baseline data gathered previously.
- To determine how the current waste and recycling industries can best benefit from the data and predictions made during the research.

The structure of the thesis is:

**Chapter 1** introduces the field of waste management and recycling that relates to plastic film.

**Chapter 2** discusses the polymer chemistry and associated science that relates to the microstructure of plastic materials.

**Chapter 3** reviews the current industrial practices for the manufacture and recycling of plastic materials.

**Chapter 4** illustrates the design procedure that was used to devise the experimental testing including a review of previous similar work.

**Chapter 5** details experimental methodology of the tests that were performed on the plastic materials used in this work.

**Chapter 6** presents the experimental results.

**Chapter 7** evaluates whether feasible applications and products can be made from the waste films and what can be done with ay residue, including two recycled engineering products that were tested.

**Chapter 8** uses the experimental results to develop a predictive model than can estimate the effect of recycling on plastic film materials and to develop a series of performance envelopes such that these factors can be tolerated and to determine how much degradation of the film results from typical life-cycles.

**Chapter 9** models the economics of plastic film recycling and determines whether such processes are economically sustainable.

**Chapter 10** discusses the impact of the investigations made.

**Chapter 11** Concludes on the study and makes recommendations for future work.

# Chapter 2 – Polymer science

## 2.1 Introduction

This chapter is concerned with introducing the chemistry responsible for the physical properties of plastic materials and the molecular-scale processes which occur during the manufacture of such products. It also introduces the industrial processes that are traditionally used to manufacture these different products. The inputs to such processes are normally virgin plastics. With some process modification it is possible to utilise reclaimed (i.e. waste) material in the same manufacturing processes.

Before embarking on a study of plastics recycling it is important to introduce the molecular-scale chemistry that is occurring in order to understand why some recycled products behave in a particular way. The internal structure of plastic materials have a significant effect on their mechanical properties, so the understanding of this structure is key in explaining many of the results from experimental work. It is also helpful to show how these physical properties can be measured.

## 2.2 Basic concepts

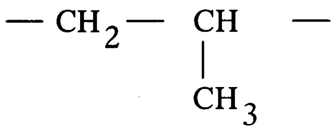
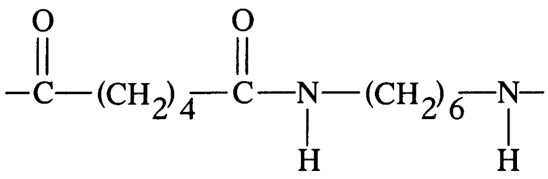
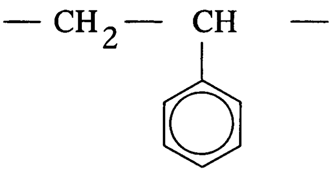
A polymer is defined as a large organic molecule built by the repetition of smaller chemical units called monomers. The monomers, made up of atoms, bond together covalently to form a polymer that has a carbon backbone. The repeating units of some common polymers is shown in

Table 2.1. The term polymer is often used for engineering materials known as "plastic", but many biological and inorganic molecules are also polymers. All plastics are polymers, but not all polymers are plastics. The term "plastic" more commonly refers to the way a material behaves under applied forces or during melting.

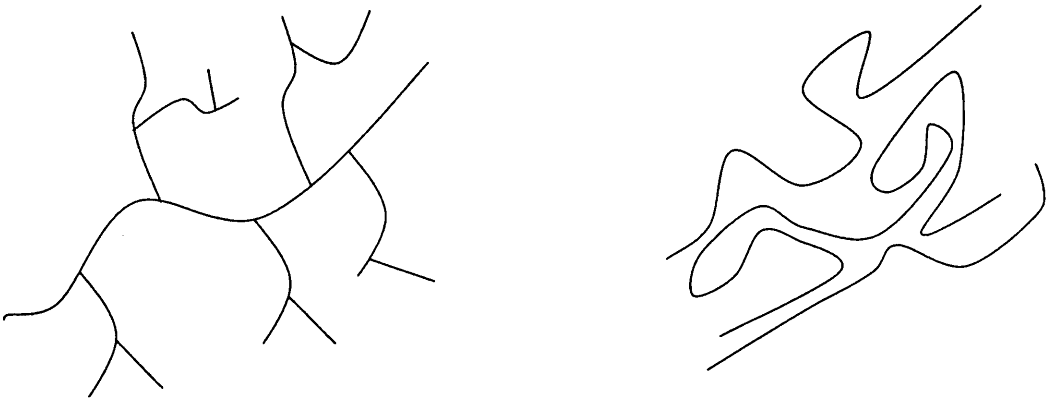
Polymers consisting of the repeating units of one kind are called homopolymers. If various different groups are present in the same molecular chain, it is referred to as a copolymer. The length of a molecular chain can vary, but materials having a molecular weight of less than 1,000 are rarely of technological interest [29].

Polymers can exist as single molecules or as molecular networks. Single molecules can either be linear or branched, as shown in Figure 2.1 [30]. Linear polymers contain no side-chain branching and are thus single strands. This can account for some of their physical properties, as discussed later in this chapter. Branched polymers have side-chains connected to the main backbone of the original chain, in some cases the polymer will branch further, making the structure appear tree-like in its configuration. The amount of side-chain branching and the lengths of the branches is not always the same and so some polymers can appear to be randomly branched. The branching mechanism can depend on a number of factors, for example composition of the monomer, catalysts used in its manufacture and processing conditions.

Table 2.1 Repeating units of some polymers.

| Polymer | Repeating unit |
|---|---|
| Polyethylene<br>(PE) | $-CH_2-$ |
| Polyvinyl Chloride<br>(PVC) | $-CH_2-\ CH\,Cl-$ |
| Polypropylene<br>(PP) |  $-CH_2-\underset{\displaystyle CH_3}{\underset{\vert}{CH}}-$ |
| Acetal | $-CH_2-\ O-$ |
| Nylon 6/6 |  $-\overset{\displaystyle O}{\overset{\Vert}{C}}-(CH_2)_4-\overset{\displaystyle O}{\overset{\Vert}{C}}-\underset{\displaystyle H}{\underset{\vert}{N}}-(CH_2)_6-\underset{\displaystyle H}{\underset{\vert}{N}}-$ |
| Polystyrene<br>(PS) |  |

Another important physical property is crystallinity. Polymers in the solid state can also be completely non-crystalline (amorphous) or can show some degree of crystallinity. A useful analogy to describe the molecular state of an amorphous polymer is that of a randomly arranged bucket of worms. The intensity of the movement of the polymer links, i.e. segmental Brownian motion, increases with temperature. Below a certain temperature, known as the glass transition temperature, the polymer segments do not have sufficient energy to move past each other, thus the polymer is rigid and brittle. Crystalline polymers consist of small crystallites that act as cross-links, restraining the movement of the molecular chains and thus contributing to the strength and stiffness of the material.



(a) Linear Polymer (b) Branched Polymer

Figure 2.1 Classes of polymers

Plastics made up of unlinked polymers are called thermoplastics. These materials melt on heating and solidify when cooled, allowing them to be processed in the molten state a number of times. This is because they have a large degree of mobility in the molten state, on account of the motion not being restricted by cross-links. Common thermoplastics include Polyethylene, Polypropylene, Polyvinyl Chloride and Polystyrene.

If the polymer is highly cross-linked, the chains cannot slide past one-another, although some flexibility is maintained in sections remote from the links. At the appropriate temperature, the cross-linked polymer may become less rigid or rubbery. As the degree of cross-linking increases, so does the glass transition temperature. Eventually the glass transition temperature exceeds the decomposition temperature of the polymer, such that the polymer will oxidise (burn) rather than melting.

Such a polymer can exist only in the glassy state. Plastics based on polymers containing irreversible cross-links are called thermosets. Once the thermoset has been processed into the final product it cannot be melted and reprocessed. This is an interesting point to note, as many plastics recycling processes require melting of some kind [29]. Thermosets are usually synthesised in-situ directly into the finished product, rather than synthesised before re-melting or moulding as in the case of thermoplastics. Common thermosets include Phenolics, Amino plastics, Polyesters, Polyurethanes and Epoxies.

## 2.3 Polymer morphology

The idea that polymer matrices are either amorphous (random) or crystalline (aligned) is an idealised one and in reality all polymers exist as a mixture of the two. The physical characteristics of a polymer depend on the relative amounts of crystalline or amorphous structure that the polymer chains are arranged in. Often this is referred to as the percentage crystallinity and is an indication of the material properties of the polymer [30]. The realistic structure of polymers consists of crystallite nodes suspended in an amorphous matrix, as depicted in Figure 2.2.

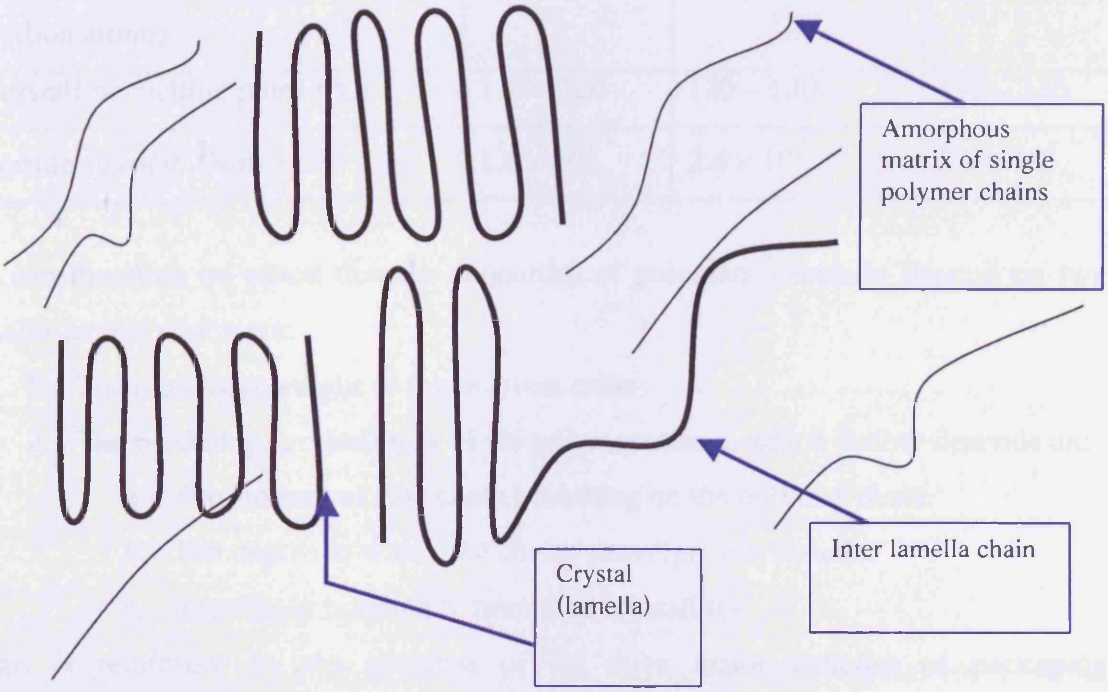


Figure 2.2 crystalline lamella polymer chains suspended in an amorphous matrix.

The lamella crystals are formed when polymer chains fold in on themselves during cooling or synthesis. The folded crystals are more compact than the spread open amorphous chains and thus are more difficult to mobilise. Generally speaking, the more crystallinity in a polymer, the more energy is required to mobilise the crystalline chains and as a result a high percentage crystalline polymer is less flexible and has a higher melting point.

Branching of polymer chains can have a profound effect on the morphology of the resulting matrix. Highly branched molecules, such as LDPE, are far less likely to form crystalline lamella because the side chains inhibit regular stacking geometry. This is further illustrated by the data in Table 2.2, as it shows a direct relationship between side chain branching, crystallinity and mechanical properties. For example, HDPE has less than 0.5% side-chain branching and up to 80% crystallinity, whereas LDPE can have up to 3% side-chain branching and only 53% crystallinity.

Table 2.2 Crystallinity and some properties of polyethylenes.

| Properties | Polyethylene | | |
|---|---|---|---|
| Type | Low density | Medium density | High density |
| Approximate crystallinity (%) | 42 – 53 | 54 – 63 | 64 – 80 |
| Branching ($CH_3$ groups per 1000 Carbon atoms) | 15 – 30 | 5 – 15 | 1 – 5 |
| Crystalline melting point (°C) | 110 – 120 | 120 – 130 | 130 – 136 |
| Tensile strength ($N/m^2$) | $1.6 \times 10^7$ | $2.4 \times 10^7$ | $3.8 \times 10^7$ |

It can therefore be stated that the properties of polymers generally depend on two major factors which are:

1. The molecular weight of the polymer chain.
2. The percentage crystallinity of the polymer matrix, which further depends on:
    a. The amount of side chain branching on the polymer chain.
    b. The degree to which the chains can align into lamella.
    c. Inter-chain bonding between the crystallites.

This is reinforced by the sketches of the three major varieties of packaging polyethylene shown in Figure 2.3.

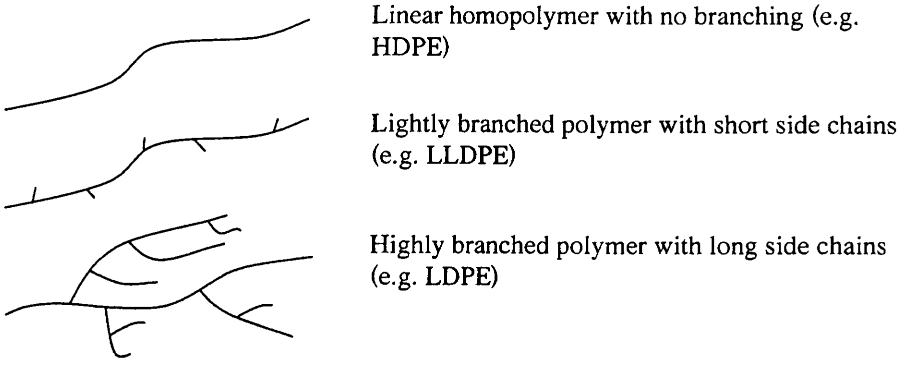


Figure 2.3 Chain branching in polyethylene [30].

The molecular-scale processes that govern when and how these factors arise are beyond the scope of this work, but their identification is important because they govern the polymer properties and therefore must be determined.

This relationship is further presented as a phase chart in Figure 2.4 [31]. As stated above, the crystallinity and molecular weight of a polymer determine its physical properties. The figure shows low crystalline, low molecular weight polymers such as LDPE are soft and flexible, whereas highly crystalline, larger molecules are harder. The bottom-right quadrant of the plot, where the polymers are low in crystallinity, but larger in molecular weight can give rise to materials which are either hard and brittle or limp and flexible. This is attributed to the configuration of the molecular chains i.e. the degrees of side branching and cross-linking.

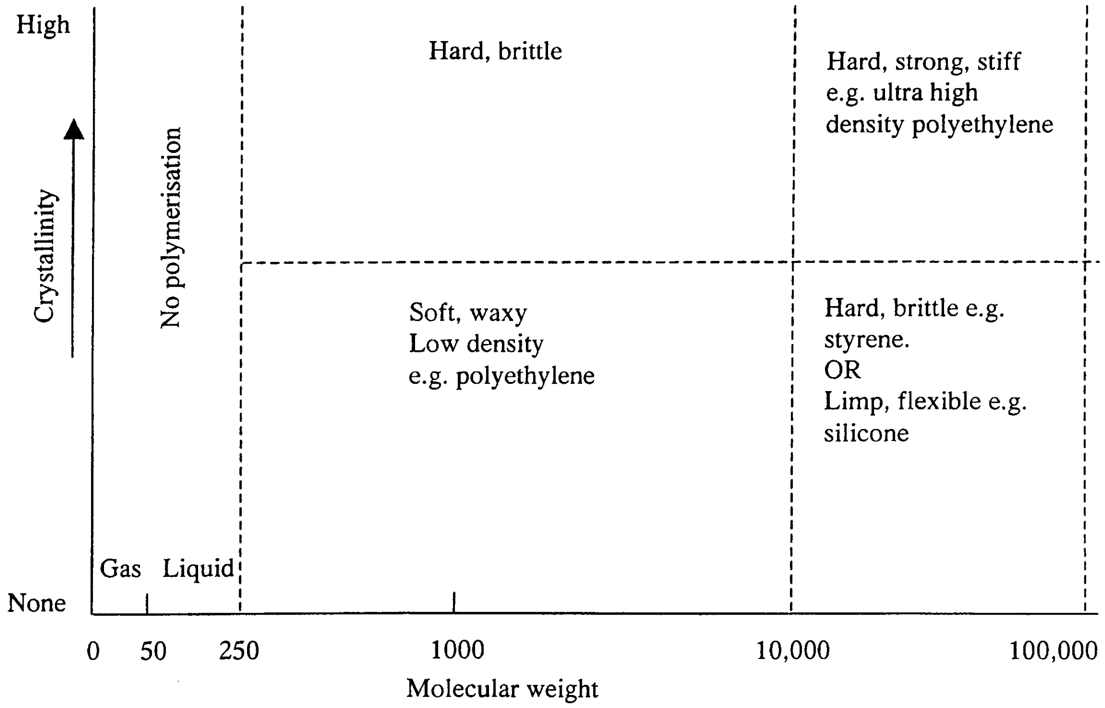


Figure 2.4 Relationship between crystallinity and molecular weight for polymers

Crystallinity of polymers can be changed and influenced through processes such as extrusion and drawing. Oriented polymer fibres are obtained by drawing a molten amorphous polymer through a die, which can orientate the polymer chains in the direction of drawing. This is often seen in blown-film products, where a thin film is formed by extrusion through a narrow orifice and thus mechanical properties are measured both parallel and perpendicular to the direction of extrusion.

## 2.4 Measuring polymer crystallinity : X-Ray Diffraction (XRD)

If the crystallinity of a polymer is critical in understanding its physical properties, then it is essential to be able to measure the property in a consistent manner. A widely used method to determine the degree of crystallinity is by X-ray diffraction. An X-ray diffractometer is a device that projects X-rays onto a sample and collects the rays diffracted at a number of angles by employing a detector that can sweep in an arc. A real 3-dimensional crystal contains many sets of planes. Figure 2.5 shows a schematic of a typical X-ray diffractometer.

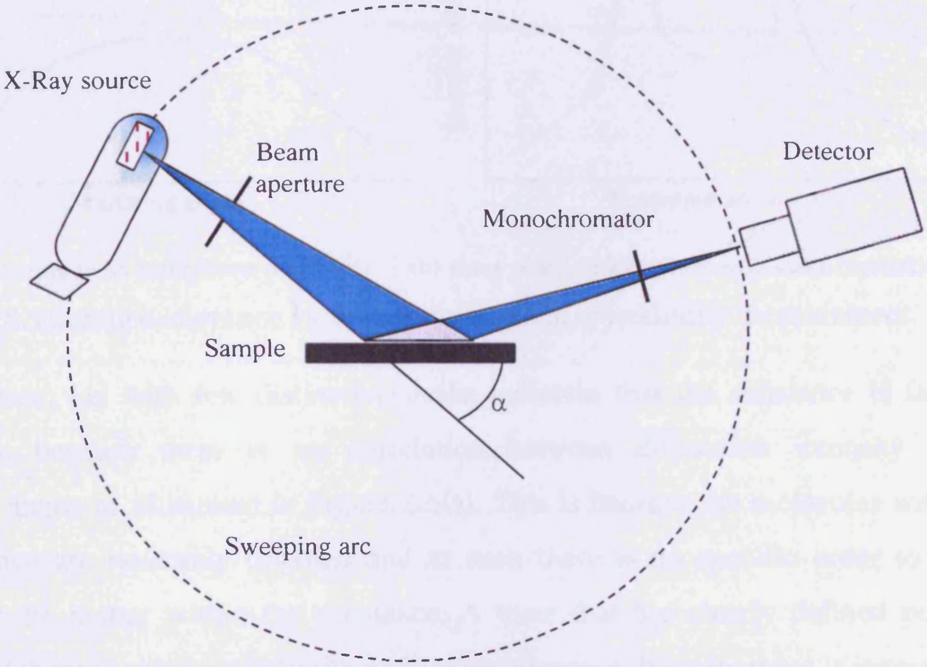
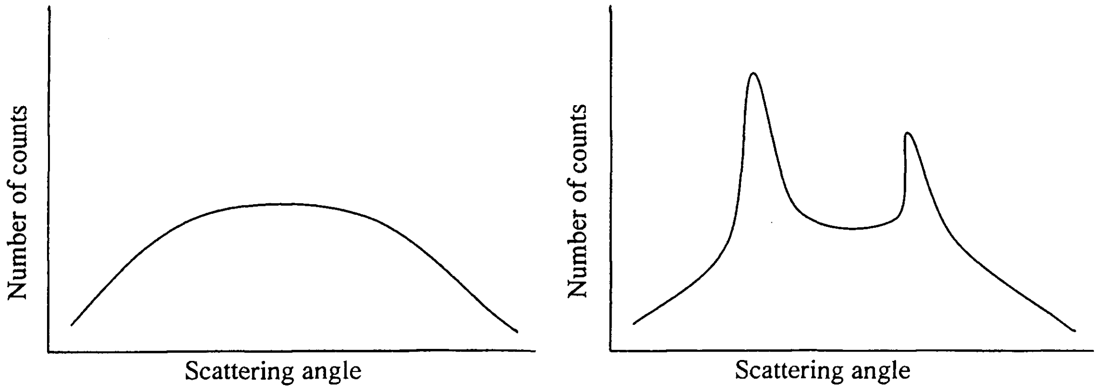


Figure 2.5 schematic operation of an X-Ray Diffractometer

For diffraction, a crystal must have the correct orientation with respect to the incoming beam, such that only aligned crystals will allow the passage of the beam. The greater the intensity of the diffracted rays at a particular angle, the more the crystals are aligned toward it and thus the greater amount of crystalline structure at that orientation. The diffraction angle of the X-ray on leaving the substance is a function of the distance between the crystal planes. The larger the diffraction angle, the further apart the crystal planes are.

Results from this apparatus are given as plots of intensity versus detector angle. Figure 2.6 shows a pair of typical plots of occurrence versus scattering angle for two polymers. Such results are often presented in terms of the ratio of occurrence to the value of the highest peak, i.e. the highest peak has a value of 100% and other values are expressed as a percentage of this. It can be seen that the trace in Figure 2.6(a) is smooth and broadband, whereas the trace in Figure 2.6(b) has two clearly defined peaks at two different diffraction angles. The detector angle is used to calculate the crystal lattice spacing, which is usually expressed in Angstroms (1 Å = 1 x $10^{-10}$m).



(a) broad scattering in an amorphous polymer (b) sharp peaks in a polymer with some crystallinity

Figure 2.6 Scattering occurrence vs. scattering angle in crystallinity measurement.

A broad trace, i.e. with few distinctive peaks indicates that the substance is fairly amorphous, because there is no correlation between diffraction intensity and diffraction angle, as illustrated in Figure 2.6(a). This is because the molecules within the substance are randomly oriented and as such there is no specific order to the packing of the matter within the substance. A trace that has clearly defined peaks implies that there is some crystallinity within the substance, because there is increased diffraction at some angles of x-ray incidence, as illustrated in Figure 2.6(b). This trace shows that the substance in question has two dominant crystal structures with different spacing, as shown by the two peaks in the diagram.

Of principal importance in the study of polymer degradation is the change in crystallinity as the polymer undergoes physical processes, such as thermal recycling. To find the percentage crystallinity a mathematical deconvolution of the results and the area under the crystalline peaks is performed, usually with a computer program. This result can be expressed as a ratio of the crystalline peaks to the broadband background scattering from the amorphous portion.

This gives an indication of the percentage crystallinity in a polymer and is used in conjunction with mechanical testing to judge whether the polymer will be suitable for an application, or how the polymer has changed during a process. Should the application require a softer or more ductile polymer then a substitute could be selected that has less crystalline characteristics.

## 2.5 Measuring polymer molecular weight - Gel Permeation Chromatography (GPC)

Knowledge of the molecular weight and distribution in a polymer helps to predict the material properties and potential applications. When assessing the effects of recycling, knowing how the molecular weight changes with recycling gives an indication as to the changes to the polymer chains. In polymer chemistry, Gel Permeation Chromatography (GPC) also known as Size Exclusion Chromatography (SEC) is used to find both the weight and the weight distribution of the polymer chains. It is a method in which molecules are separated based on their size. This method is accepted as the most reliable way of determining the molecular weight distribution of a polymeric material.

In GPC, a column is packed with a porous material (typically silica or crosslinked polystyrene) and solvent is forced through the column. A sample is dissolved in this solvent and is then introduced into the flow running through the column. A detector monitors the concentration of sample exiting the end of the column.

Inside the column, the dissolved molecules are separated based on their hydrodynamic volume, which is defined as the volume the molecule occupies in a dilute solution. This is because the smaller molecules are more likely to dissolve through the porous material and thus are extracted earlier. Larger molecules take longer to dissolve through the porous bed and thus are detected later on.

By studying the properties of polymers in particular solvents and by calibrating each column setup with samples of known molecular weight, it is possible to get a relative distribution of molecular weights for a given polymer sample. Using this data, it is possible to calculate average molecular weight and Polydispersity Index (PI), which is the ratio of the weight average molecular weight to the number average molecular weight, indicating the distribution of individual molecular weights in a batch of polymers, as shown in equation 3.1.

$$PI = \frac{\bar{x}_w}{\bar{x}_n} = \frac{\sum\left(\frac{n_x}{N}\right)x}{\sum\left(\frac{w_x}{w}\right)x} \qquad \text{Equation 3.1}$$

Where $x_w$ = weight average of molecular weight

$x_n$ = number average of molecular weight

$n_x$ = squares of molecular weights in sample

$w_x$ = molecular weights in sample

N = square of number of samples

w = number of samples

This must be done to within a useful level of accuracy. An overall schematic of the GPC process is shown in Figure 2.7.

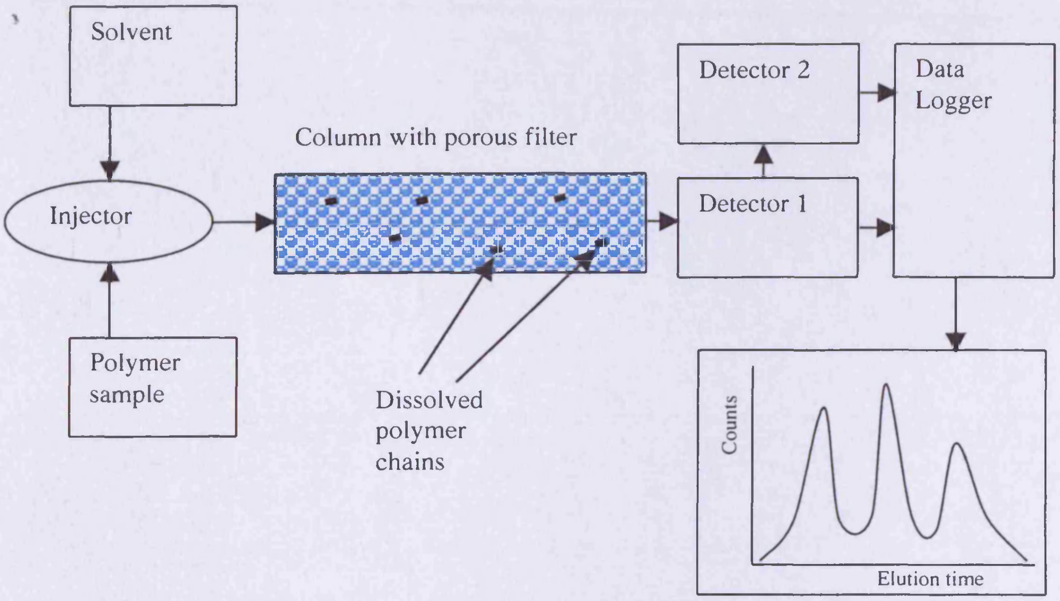


Figure 2.7 Schematic of the operation of Gel Phase Chromatography apparatus.

## 2.6 Processing and manufacture of thermoplastic products

As discussed earlier in the chapter, thermosetting polymers are virtually impossible to thermally recycle and as such are of limited interest in this work. For this reason only techniques for the production of thermoplastic polymers will be covered. In all of the techniques given below, the input feedstock to the manufacturing processes will be plastic in the form of either powder, or more commonly pellets. The process of producing these feedstocks (powder or pellets), i.e. extracting light fragments of crude oil, processing these chemicals into monomers, polymerisation and manufacture into pelletised plastic shall not be covered for brevity. Recycling processes such as grinding and pelletising are covered in Chapter 3. There is a multitude of techniques for producing finished products from plastic feedstocks and only the most common will be discussed in this chapter, as novel and advanced processes are beyond the scope of this work.

### 2.6.1 Extrusion

Extrusion normally requires a large amount of force, usually from a screw that pushes the pelletised or powdered feedstock through a die, which is a shaped orifice that determines the shape of the product. The plastic is melted and forced through the die as a continuous piece and cut to length as required. Extrusion is generally used to produce pipes, tubes, sheets and wires. More modern and efficient processes melt the polymer from pressure applied by the screw, but heat may be added during the processes to cause the feed plastic to melt if there is insufficient energy transfer from the screw. Figure 2.8 is a schematic of a screw extrusion moulding machine.

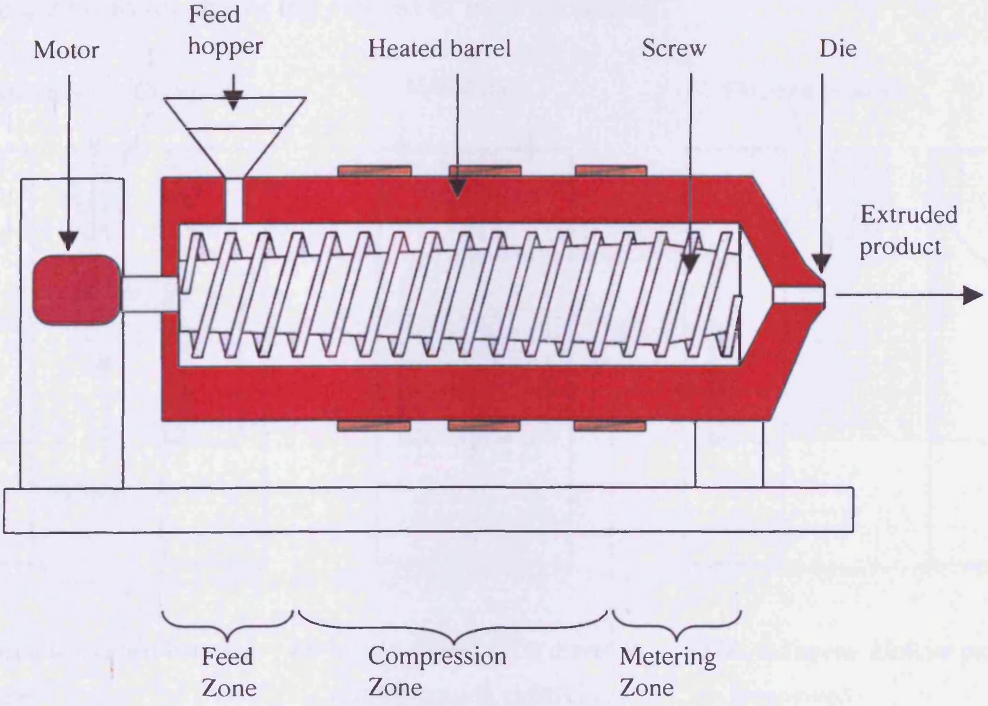


Figure 2.8 A screw extrusion moulding machine.

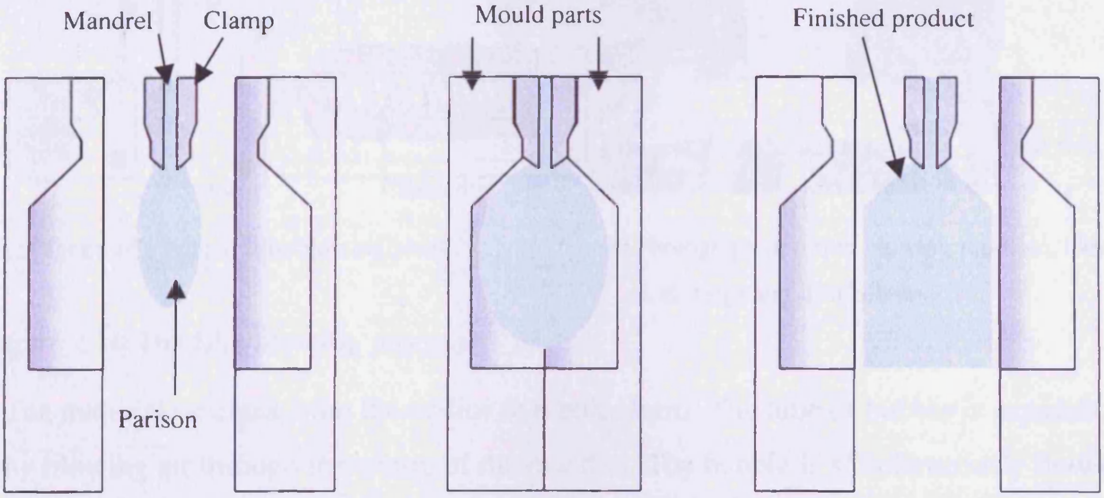
The feed zone is located in the rear of the barrel. The input material is fed in via a hopper and mixed by the action of the screw. In the transition or compression zone the granules are compressed and air is purged back through the hopper. While the material is being compressed and moved forward, it is also being heated, partly by conduction from the barrel heaters, but mainly by friction from the shear forces of the screw. As it melts, it is also mixed into a homogenous melt. The metering zone provides polymer melt stability and helps ensure a uniform delivery rate. It is in this zone that any melt filtering occurs, should there be contamination in the material that is being processed, as can be the case with recycled material. From this zone the molten material passes out via the die.

### 2.6.2 Injection moulding

Injection moulding machines are similar to extrusion machines, but in the injection case, the resin is forced into a specially designed mould. After the melt has cooled and solidified, the mould opens and the part is ejected. Injection moulding can be used for both thermoplastics and thermosets. In the case of thermoplastics, material is melted in the injection barrel and solidifies on cooling in the mould. Injection moulding is versatile process normally used to produce solid components but there is a general limit to the size of component produced because of thermal stresses during cooling.

### 2.6.3 Blow moulding

Figure 2.9 (a) to (c) shows the process of blow moulding.



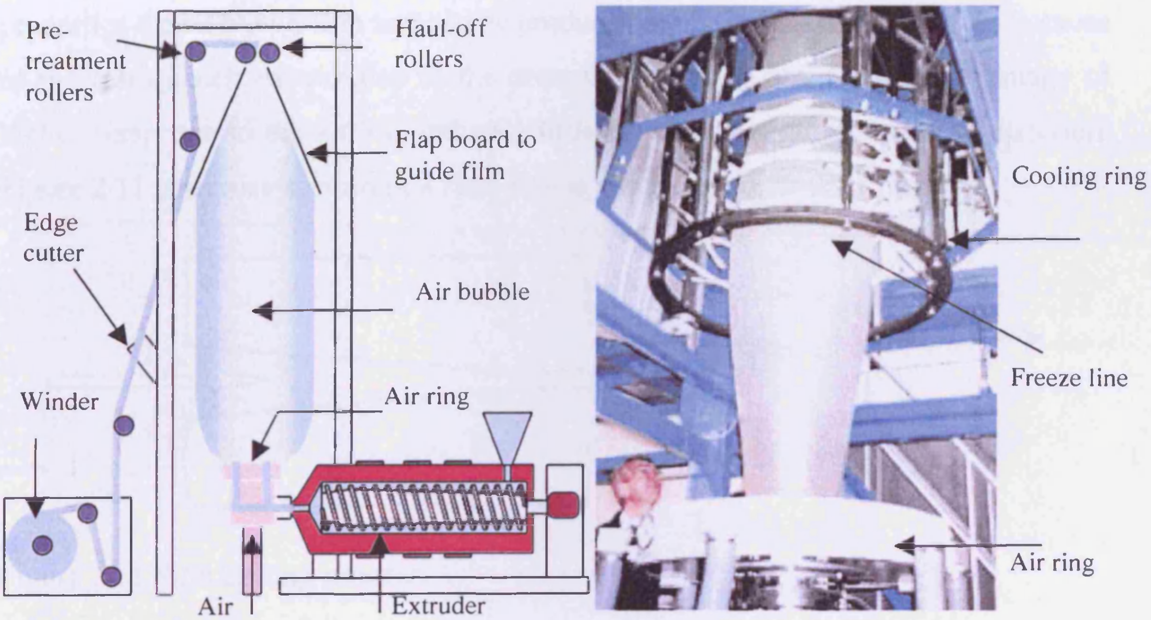
(a) Parison is injected between mould. (b) Mould closes. Air is driven in causing parison to fill cavity (c) Mould opens. Hollow product is removed.

Figure 2.9 The three stages of blow moulding.

Blow moulding begins with the manufacture of a parison, which is like an un-inflated balloon. The parison is formed normally by extrusion into a pipe, which is then sealed at one end. The parison is then inflated by a mandrel (A metal cavity around which the plastic material may be shaped) to the required shape inside a mould, which is the shape and size of the final product. Blow moulding is used in many applications, most notably the manufacture of liquid containers such as bottles.

### 2.6.4 Film blowing

Blown film extrusion is a continuous process in which the film is produced by forcing molten material through a die and around a mandrel. A single screw extruder is used to melt the polymer and pump it into the mandrel, as shown schematically in Figure 2.10(a).



(a) Diagram of a typical film blowing plant

(b) Photograph of a film blowing machine, looking at air rings and film bubble.

Figure 2.10 The film blowing process

The material emerges from the orifice in tubular form. The tube or bubble is expanded by blowing air through the centre of the mandrel. The bubble is simultaneously drawn axially and expanded radially through the annular slit die to get the desired film thickness. Extension of the melt in both the radial and downstream direction stops at the freeze line due to solidification of the melt. The bubble is cooled by an air ring on the outside. The nip rolls collect the film, as well as sealing the top of the bubble to maintain the air pressure inside. A photograph of this process is shown in Figure 2.10(b), the freeze line is visible just below the upper cooling ring. The majority of polymer films are manufactured by blown film extrusion, especially those with a small film thickness. Most blown film processes use a vertical upward configuration but there are some processes that use a horizontal or vertical downward configuration.

### 2.6.5 Film casting

Film casting is generally used to produce thicker film profiles of around 1mm thickness and above. In the cast film process the material is forced through a slit die to form a sheet. The sheet is (as with blown film) drawn off via nip rolls again the wall thickness is determined by the speed at which the material is drawn off. This process, although similar to film blowing, does not use any auxiliary air to chill the plastic. Despite being easier to set-up and run than blowing, casting is not as effective at making thin, wide film profiles. A cast film generally has much better optical properties than a blown film and can be produced at higher line speeds, this is because of the fast quench capabilities of the process. However, it has the disadvantage of higher scrap due to edge-trim, and very little film orientation in the cross-direction. Figure 2.11 is a cross-section of a film casting die.

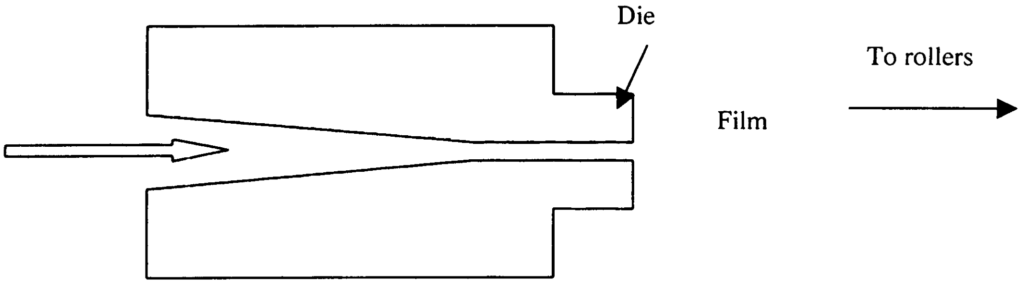


Figure 2.11 Film casting process.

### 2.6.6 Rotational moulding

Rotational moulding is used mainly for the production of hollow objects from thermoplastics, and to a lesser extent, from thermosets. The equipment used is relatively low cost and durable. Plastic powder or liquid is placed in a mould which are then rotated whilst heated. The powder melts and coats the surface of the mould. If reactive liquid resin is used, it solidifies on contact with the hot surface.

### 2.6.7 Compression or transfer moulding

In compression moulding plastic material is placed directly into a heated mould. Pressure is then applied, forming the finished product along with excess mould flash. A further development of compression moulding is transfer moulding. Raw material is placed into a heated transfer case. After the material has begun to melt, it is placed into heated moulds by means of a ram. The transfer of the substance creates heat which in turn causes the plastic to take the shape of the mould. Products produced by compression moulding include dishes, handles, container caps, and washing machine parts. Costs involved with compression moulding are low due to the simple nature of the process.

### 2.6.8 Thermoforming

In the thermoforming process thermoplastic sheet is formed into a product by first being softened by the application of heat, and then shaped by the application of pressure and by pressing the hot sheet against the cold mould. Forming pressure may be developed by vacuum, compressed air or mating with a matched mould. Vacuum forming is sometimes used to make bowl and tray shaped products.

### 2.6.9 Film lamination

Films can be combined with other types of films or substrates such as aluminium foil or paper to achieve a specific property. Films such as LDPE, HDPE and PVC can be combined under heat and pressure without the use of adhesive. This process is used commonly in the food packaging industry [32]. It is worth noting at this point that laminated products can cause difficulties during recycling processes, as the contaminants (such as aluminium foil) are bonded directly to the plastic and the removal of these laminated materials is not straightforward.

## 2.7 Summary

This chapter has introduced two key aspects of plastics science:

- The polymer chemistry behind the science of plastics processing.
- The processes required to produce a commercial product from a plastic feedstock.

It is important to understand the polymer chemistry of plastics for a recycling study in order to qualitative explain physical property behaviour during the recycling processes, which are akin, but not identical, to the initial manufacturing process. To this end, changes or anomalies in mixtures can be better understood when looking at the process on a molecular level.

Not all plastics can be traditionally recycled using heat and pressure. Highly branched or thermosetting polymers will burn rather than melt, which will cause problems in the recycling process. It is therefore important to understand the molecular chemistry of such materials, should there be problems of this nature during recycling tests.

This chapter has also shown that the measurement of molecular properties must be carried out with specialist equipment and done so to the highest of standards if useful data is to be produced. Properties such as side chain branching, molecular weight and crystallinity rely on measurement scales of a few angstroms, which is in great contrast to the scale of a large-batch process such as waste recovery.

# Chapter 3. Review of industrial recycling practice

## 3.1 Introduction

The purpose of this chapter is to present the current methodology in the industry for plastic recycling in terms of technologies and practice. The actual procedures undertaken in a recycling plant are key to the entire recovery operation and should be understood such that they can be used in conjunction with information about the internal chemistry of the polymers themselves.

There are two main processes that occur in plastics recycling, namely separation and remanufacture. Separation is often misconstrued by the public as 'recycling', when in effect it is the classification of material types prior to production. Remanufacture is the process whereby waste plastic material is made into a new product. Polymer separation technologies and the three principal methods of polymer remanufacture are presented herein.

Also highlighted are the operation of two recycling plants, one that produces rigid plastic and one that remanufactures film, visited over the 2002 – 2003 period. Both plants used a limited amount of separation and mechanical recycling with heat addition to process the waste material. The plants were self-sustaining businesses that relied on sales rather than government grants to operate and had been in existence for at least 10 years.

## 3.2 The numbering system

When working with plastics there is often a need to identify which particular plastic material (polymer type) has been used for a given product. Most consumers recognise the types of plastics by the "recycling arrows" numerical coding system created by the Society of the Plastics Industry in 1988 [33]. There are six different types of plastic resins that are commonly used to package household products. The identification codes listed in Table 3.1 can be found on the underside of most plastic packaging. Preliminary research has shown that most plastic film products do not carry resin codes, which has been attributed to a range of reasons, e.g. interfering with optical properties and aesthetics.

Table 3.1 Resin codes for common plastic packaging.

| Number | Abbreviation | Resin |
|---|---|---|
| 1 | PET | Polyethylene Terephthalate |
| 2 | HDPE | High-Density Polyethylene |
| 3 | V | Vinyl/Polyvinyl Chloride |
| 4 | LDPE | Low-Density Polyethylene |
| 5 | PP | Polypropylene |
| 6 | PS | Polystyrene |
| 7 | OTHER | Usually layered or mixed plastic. No current recycling potential |

The resin codes are meant to indicate the type of plastic, not the ease of which it can be recycled. PET and HDPE are the most commonly recycled polymers. LDPE is at present less commonly recycled. The other types are generally not recycled in large volumes, except perhaps in smaller programs such as recycled stationery from PS vending cups [34]. Common engineering plastic polycarbonate (PC) and Acrylonitrile-Butadiene-Styrene (ABS) do not have recycling numbers as their recycling is not straightforward. Most work and debate in plastic recycling focuses on the seven categories identified in Table 3.1.

### 3.2.1 Uncoded plastics

Plastic consumer goods not identified by code numbers are not usually collected for municipal recycling. Plastic sheets (such as tarpaulin), pipes, toys, electrical products and others simply do not fit into the numbering system that identifies plastics used in consumer containers. There are thousands of different varieties of plastic resins or mixtures of resins. These are developed to suit the needs of particular products. There is limited recycling of some of these specific plastic products from industrial sources. No evidence has been found to suggest that any UK company is in the business of collecting a variety of these plastics for recycling without resin codes. A generally accepted belief is that mixed plastics with an unknown composition would make an unsaleable product with unpredictable and inconsistent material properties.

## 3.3 Biodegradable plastics

Since a large volume of domestic waste is made up of plastics there is a great deal of interest in recycling and in producing plastic materials that can be safely and easily disposed of in the environment.

One option is to produce polymers that are truly biodegradable, and which may be used in the same applications as existing polymers. The requirements for such materials are that they may be processed through the melt state, that they are impervious to water, and that they retain their integrity during normal use but readily degrade in a biologically rich environment.

Polyhydroxyalkonates are a family of naturally occurring polyesters, produced in the form of carbon storage granules by many bacteria. Zeneca Bioproducts is currently producing these polymers on a pilot plant scale under the trade name BIOPOL™. The Bristol Polymer group [35] has been actively involved in the development of these polymers, especially in determining optimum processing conditions.

Polycaprolactone is a petrochemically based compound that can be moulded, extruded or blended with starch. Its original applications were for stiffeners in running shoes and casts. In combination with starch it is currently being used for compost bags and disposable cutlery [36].

There have been a number of developments using existing production capacity that have produced biodegradable resins from synthetic sources. DuPont, Bayer and Eastman have all begun production of such compounds. These polyester based polymers achieve biodegradability successfully, but there are still question that the price level will ever allow consumer acceptance of these products [36].

## 3.4 Separation

One of the biggest problems in plastic recycling is the incompatibility of resin types. The complex nature of the polymeric structure of plastics means that incompatible polymer types can be prone to chemical reaction when in the molten state. This means that mechanical recycling of different resin types can lead to an unusable material or potentially harmful emissions, as in the case of co-melting PET with PVC, which produces harmful chlorine compounds.

It is an accepted fact within the plastics recycling industry that recycling is only economically and technically feasible if the resin types are separated into their individual streams otherwise a saleable product is unlikely to be produced. For this reason some form of separation is required at some stage of the recycling process for plastic. There are a number of methodologies available to the recycler in order to segregate feedstocks into individual polymer streams. The following section outlines common practices and emerging technologies.

### 3.4.1 Manual separation

The most simple and perhaps crude method of plastics separation can be performed simply by placing large numbers of human operatives along a picking conveyor belt to determine the composition of the material by visual inspection. This technique is aided by clear and consistent labelling of the products that are being picked. Hand sorting is mostly undertaken in poor and developing countries such as China. In developed countries such as the UK, the economics of this process (i.e. human resource costs) usually cause manual separation to be economically infeasible, whereas labour costs in poorer countries are substantially less. Figure 3.1 shows a very crude manual sort in the Philippines and a conveyor-based system in the USA. Manual sorting of plastic in third world countries has come under scrutiny from human-rights groups because of working conditions and low wages [37]. Chinese companies are able to sort and recycle plastic wastes for such a low cost that British companies are starting to go out of business, due to the higher prices paid by Chinese rivals. For this reason increasingly larger amounts of plastic for recycling are being transported the 8,000 mile journey to China, which is having a serious economic and environmental impact [38].

Figure 3.1 Examples of manual sorting technologies
(a) manual sorting in the Philippines (b) conveyor sorting in the USA

### 3.4.2 Floatation

Floatation is a fairly simple method of plastic separation and is based on the differences in density between the different kinds of polymers. In this technique the plastic feedstock is fed into a large vessel containing a liquid, which is usually water. The floated materials are normally skimmed from the top of the mixture and the sunken materials are drawn away when the tank is discharged. Such facilities can also use a centrifuge rather than gravity for separation, as shown in Figure 3.2.

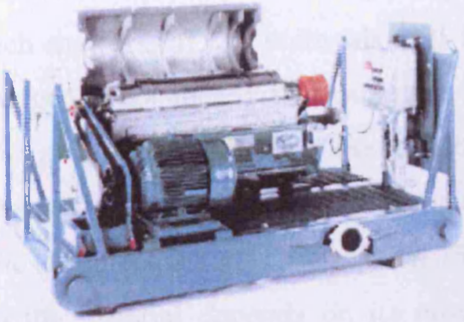


Figure 3.2 An example of a centrifuge density separation machine [39]

Usually the floatation media is water and thus only materials with a density of greater than 1000 kg/m$^3$. This is a technique commonly used to remove PET bottle flake from HDPE bottle flake. Water is not always used to separate materials and liquids with appropriate densities between those of the plastic mixture can be tailored depending on requirements. Recent research has utilised powdered chemicals that can be mixed with water to give the relevant density to separate certain plastic mixtures [40].

Another advantage of floatation, as well as its simplicity, is that the floatation apparatus can be integrated with washing apparatus. Therefore a washing and separation plant can be more cost effective than a combined washing and separation plant where a the two processes are performed separately.

One of the main drawbacks of the floatation technique is that it is poor at separating mixtures of more than two plastic types with similar density. A potential solution to this is the use of cascading floatation tanks of different liquids (i.e. different media densities) such that the end result is a group of polymers of density ranges, known as dense medium separation. However this can be somewhat inaccurate if the feedstock to the process is unknown, as well as costly due to the large number of floatation apparatus.

An emerging method in this field is froth floatation. This method works by utilising the differences in hydrophobic characteristics of polymers. The mixed plastic waste is loaded into a tank and air is bubbled through the mixture. The air bubbles then stick to the plastics at different rates, depending on how hydrophobic the polymer is.

Polymers with larger amounts of air bubbles will then float and can be classified. This technology is still not in use for large-scale plastics classification [41].

### 3.4.3 Electrostatic separation.

Electrostatic separation relies on the principle of electrostatic repulsion, when two dissimilar materials are brought together. An electronic charge will be transferred such that one of the materials will be positively charged and the other negatively charged. This means that mixtures of plastics can be separated if there are large enough differences in their electrostatic properties.

The process depends on where in the triboelectric series the two materials are situated. The triboelectric series is shown in Table 3.2. The polarity of the charge that builds up on the material depends on its position in the series, in comparison to the other material it is being rubbed against. For example, if PVC and PET are contacted together, PVC will be charged negatively and PET will be charged positively [42].

Table 3.2 Triboelectric series for common polymers.

| | |
|---|---|
| Teflon (PTFE) | Negatively charged plastics |
| Polyvinyl Chloride (PVC) | |
| Polyethylene Terephthalate (PET) | ↓ |
| Polypropylene (PP) | |
| Polyethylene (PE) | |
| Polystyrene (PS) | Positively charged plastics |

For an effective separation of two mixed plastics, the materials must be clean, dry and ground to a size of approximately 2 mm. The particles are then agitated together in a rotating drum so that charging may occur. After charging the particles are passed vertically through a strong horizontal electric field.

The positively charged particles are drawn towards the negative electrode and the negatively charged particles are drawn towards the positive electrode. The two streams are then collected in separate containers, usually by separation from some kind of adjustable arm. Figure 3.3 shows a schematic of a typical electrostatic separation system. [43].

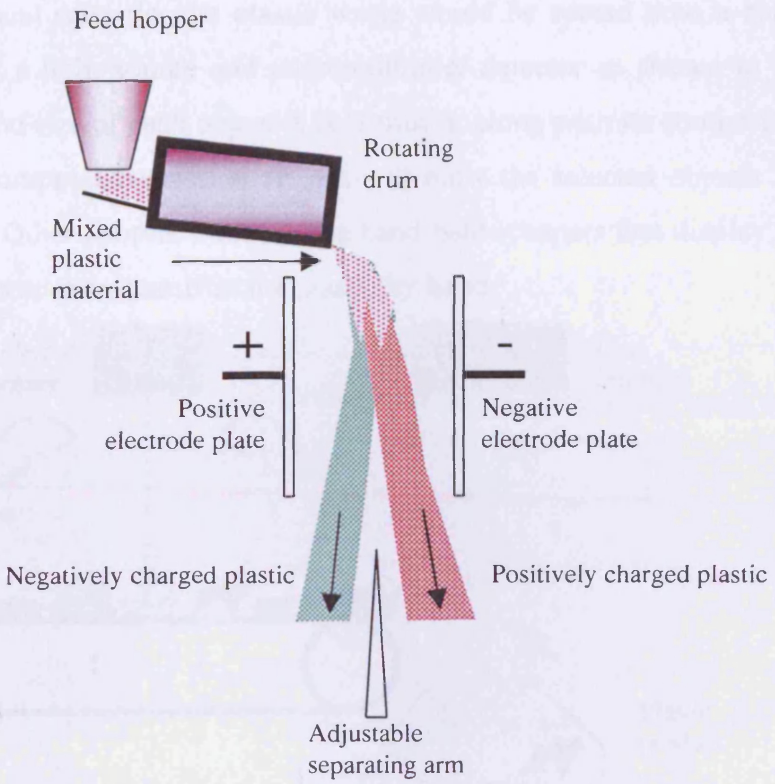


Figure 3.3 Diagram of electrostatic separation.

Electrostatic separation is being suggested as the answer to separation and recycling problems in the electronics waste sector by some industrialists. Recent recycling articles have cited this technique as a future leader for separation technology and show examples of where it is already commercially successful [44]. It is not suitable however, for separating unknown polymer mixtures, heavily contaminated mixtures or those that are diverse in composition, which is the case in municipal kerbside recycling schemes. As this is a fairly new technology, future development could provide hardware that will allow electrostatic separation to eventually overcome this challenge.

### 3.4.4 Optical techniques

Optical methods of plastic classification involve exciting the polymer with light energy of a specific wavelength and analysing its response. As with other kinds of spectrometry, the composition of the plastic (i.e. its structure and molecular weight) material will determine the wavelength at which it will absorb radiation. The response is compared to a set of wavelengths stored in a computer database, allowing the polymer to be identified quickly.

In a practical scenario, the plastic waste would be spread onto a conveyor belt and move past a light source and photomultiplier detector as shown in Figure 3.4. The position and size of each object is determined, along with its composition and a linear array of computer controlled air jets will blow the selected objects into a receiving container. Other simpler methods use hand-held scanners that display the results to an operative who then classifies the plastic by hand.

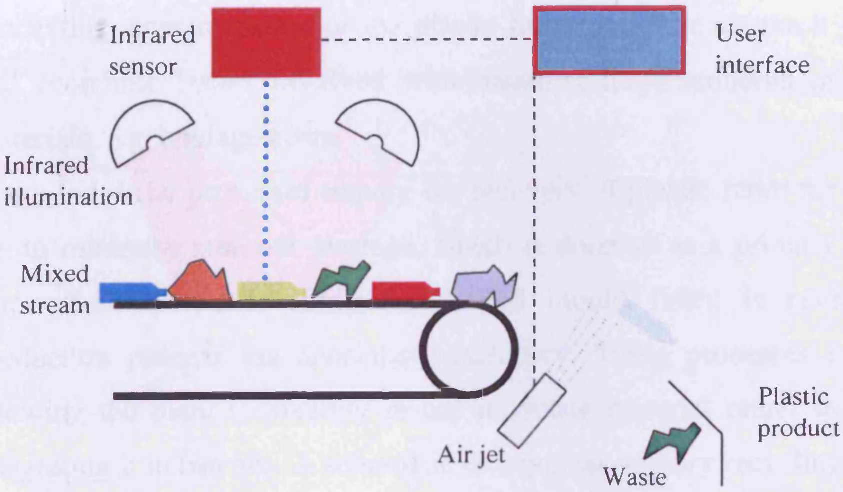


Figure 3.4 Schematic of optical sorting hardware

Although a robust method of sorting similarly shaped plastic components, optical classification can suffer accuracy problems when operated with highly contaminated recycling streams. There can also be a shape or angle-dependent scattering problem, particularly when analysing beverage containers of different shapes. For this reason many systems puncture and roll the bottles flat before passing into the analysis hardware. Optical techniques are not suited to classifying film products because of poor light scattering in thin membranes. Newer methods have developed two-colour methods that have greater versatility at less cost [45].

## 3.5 Primary recycling

Primary recycling is the reprocessing or re-manufacturing of discarded materials into the same product which can then be recycled again and as such is the simplest form of reprocessing of waste plastics into new products. Such processes involve the use of uncontaminated plastic waste to produce new components. For this reason, only thermoplastic compounds can be used as the process inevitably uses some form of heat, either by direct addition or friction. The thermoplastic can be remoulded as pure waste or mixed with other virgin polymers at various ratios. Primary recycling can be performed by the processor in plant, or through external reprocessors.

Generally speaking, primary recycling is undertaken within the factory that is producing the virgin product. Reclamation machinery is used to continuously feed the scrap material back into the process, to save on waste and thus money. Problems associated with primary recycling include degradation of material due to excessive processing, contamination of the plastic from the waste source it was obtained from and economic issues involved with handling large amounts of low bulk density materials, e.g. haulage costs.

Many industrial processes require the recovery of plastic scrap for economic reasons, i.e. to minimise material wastage, which is done so as a primary recycling process. The off-cut material, sometimes called mould flash, is re-integrated into the production process via specialist machinery. These processes can be continuous, allowing the plant to steadily re-use its waste material rather than storing and re-integrating it in batches. A schematic of a typical primary recycling activity process is shown schematically in Figure 3.5 [46].

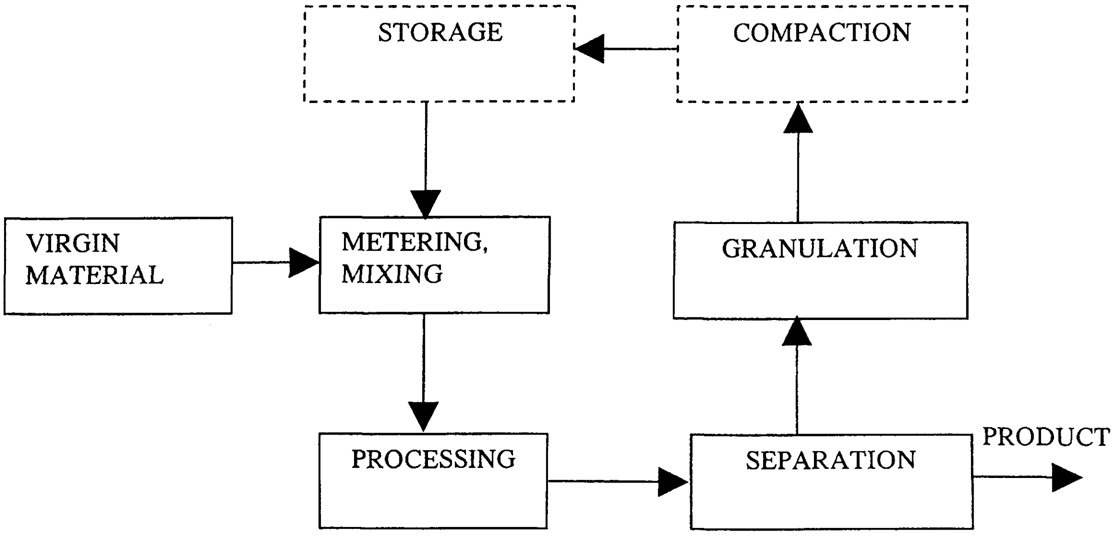


Figure 3.5 Flow-diagram treatment of a primary recycling process.

Before any plastic can reprocessed it must be granulated into a particle size close to that of the format of the original supplied resin. Granulation takes place by subjecting the material to set of steel cutting knives. There is a multitude of shredding actions, although most achieve the same result, which is to cut the material up into a fine powder. The input material is then densified, using a compactor, and then fed into a chamber where it is blended with the required amount of virgin resin.

There are many automatic scrap recycling processes available to industry, many of which require no external influence to recycle off-cuts and edge trim, a typical example being the Automatic Scrap Recycling (ASR) system produced by Process Control Corporation. A schematic of this system is shown in Figure 3.6 [47].

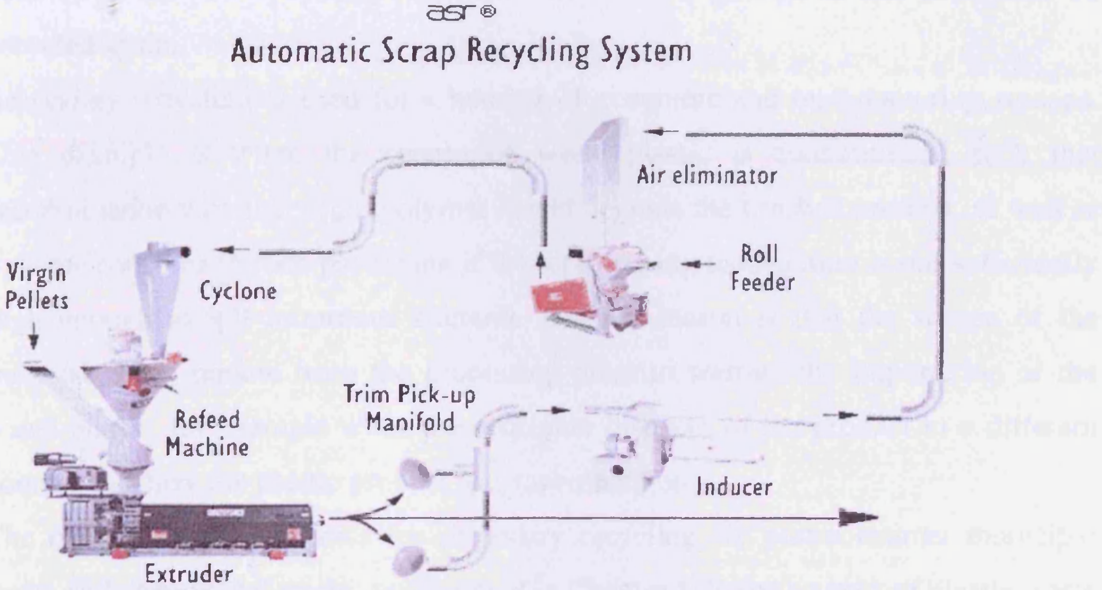


Figure 3.6 Process Control Corporation's ASR system.

Scrap material is granulated and pulled through a blower, which cools the ground plastic and feeds it into a cyclone separator to remove any dust. The scrap and virgin material are mixed in a feeder at the desired rate. The mixed materials are then fed back into the extruder where the forming process takes place. The formed material is cut to the desired shape and the waste from the product is again recycled.

More recent innovations have included the development of a material with low-temperature formability, which promises lower energy consumption in manufacture and processing, therefore improved recyclability [48]. This process makes use of a matrix of two polymers of different rheological properties that deform differently under large pressures. If this technology were to become commercially viable it would require more versatile mechanical properties in order to satisfy the requirements of packaging materials, such as gas permeability.

## 3.6 Secondary recycling

Secondary recycling is the reprocessing or re-manufacturing of discarded materials into a different product with a different application. In cases where waste plastic cannot be re-used directly in the original forming process (as is the case with primary recycling) secondary recycling is employed. Secondary recycling utilises plastic waste unsuitable for direct recombination with the feedstock polymer. Sometimes this is referred to as "down-cycling" because the recycled product is not or cannot be recycled again.

Secondary recycling is used for a number of economic and manufacturing reasons. One example is when the source of waste plastic is contaminated such that recombination with the virgin polymer would degrade the finished product, as well as hygiene concerns in food packaging if the reprocessing temperature is not sufficiently high enough to kill hazardous bacteria. Another reason is that the source of the material is too remote from the processing plant to warrant the importation of the waste plastic, for example when the consumer disposes of the product in a different country to where the plastic product was manufactured.

The main sources of plastics for secondary recycling are post-consumer municipal waste and commercial waste, as discussed in Chapter 1. Some sources of plastic waste are from industrial and manufacturing sources, which are generally preferred by secondary reprocessors because they are far more homogeneous and far less contaminated than municipal waste plastics [2].

## 3.7 Pelletising and agglomeration

Pelletisation is a key step in both primary and secondary plastics recycling. This is the stage where the raw input feedstock, be it flakes, film or unprocessed plastic products are manufactured into a homogeneous pellet that is in the same form as that of virgin plastic when it enters a manufacturing facility.

The operation of a pelletiser is quite straightforward. Material is fed into a screw extruder, similar to that described in Chapter 2, which forces the molten material through a number of dies at its outlet. As the extrudate leaves the die it is cut by a series of rotating knives. The pellets are spun off the knife blades and land in cooling water where they are transported through a trough or hose to a vibration tray. The vibration tray separates the cooling water from the pellets and delivers the pellets to a centrifuge dryer. The tray also acts to separate pellets that may have briefly adhered to one another during cutting. A centrifuge dryer spins and removes any excess water from the pellets and discharges the pellets to a transportation blower. The pellets may then be blown to a silo or resin handling system. Figure 3.7 shows an example of LDPE recycled pellets.

Figure 3.7 Recycled LDPE pellets [10].

In agglomeration processes, the plastic feedstock is impacted on its surface by slight melting or pressure, compared to pelletisation where the plastic is fully melted and extruded. The main aim of this operation is to reduce the bulk density of the feedstock, which is why agglomeration is important in plastic film recycling. Agglomerated particles are also easier to handle and measure. Filtration is not possible during agglomeration because the plastic is not melted and as such cannot flow through filter packs. This process tends to produce irregularly shaped chunks rather than uniform pellets.

There are two major types of agglomeration. In pressure agglomeration the feedstock is combined into particles via friction and shearing. In thermal agglomeration the feedstock is combined via rapid heating and cooling. This technique is especially useful in the volume-reduction of films because the surface area to volume ratio of films is very high and thus the heat energy is absorbed very quickly.

There have been recent developments in the field of pelletising / agglomerating systems such that machines are available that can perform both these tasks simultaneously, which is again useful when recycling plastic film. These machines are known as continuous agglomerator systems, or KAGs. One advantage of these systems is that they reduce the amount of gas and air transported into the extruder prior to pelletisation. Pellets that are free from gas bubbles produce a higher-quality product and thus have a higher quality and value.

## 3.8 Industrial processes

Before post-consumer and post-industrial plastics are reprocessed they are generally separated and cleaned such that the content of the feedstock is as pure as possible. Cleaning and separating is generally considered to be the most difficult and expensive part of the recycling process, which is why secondary recycled products are often less economically viable than using raw materials.

The mechanical reworking of plastics utilises the processing characteristics of waste thermoplastics and specially designed processing equipment to manufacture new products. The most commercially successful method of secondary recycling is melt homogenisation. This is a process whereby the feedstock material is thoroughly purified before processing begins, usually via melt filtration. This ensures that the finished product comprises of only one plastic compound and therefore has more desirable physical properties due to reduced contamination.

One such example of secondary recycling is the Mitsubishi Reverzer recycling machine [49]. The process involves feeding the purified plastic into a screw extruder via a hydraulic drive. The process is capable producing of cable reels, fence posts and Recycled Plastic Lumber (RPL) shown in Figure 3.8. Similar processes are used in the modern production of wood alternatives using post consumer polyethylene [50, 51].

Figure 3.8 A recycled plastic park bench made from RPL.

### 3.8.1 Primary recycling example – Frank Mercer and sons

Frank Mercer and Sons is a modern recycling company specialising in the reprocessing of polyethylene films based in Bolton, UK. The input to the process is normally post-use commercial packaging and roll-ends or aborted runs of plastic film from the manufacturing sector. The product is normally commercial damp-proof membrane of 250 μm thickness. Colour and property specification is usually achieved by masterbatching. This facility is considered as an example of primary recycling because it takes a film-based product in order to produce another one, which could in turn be recycled in the same way. Some of the material taken in by the company is post-use film and is more akin to secondary recycling, which is covered in the next section. Photographs of the plant in operation cannot be shown for reasons of commercial confidentiality.

Generally speaking the recycling process and Mercer is summarised as:

- **Feed and unbaling**

The waste input material is delivered to the site in densified bales. The bales are opened by hand and the material inside is inspected for content, colour and contamination. Excessively contaminated material at this point would be flagged for later inspection if considered too dirty for the recycling process.

- **Sorting and screening**

The material is then examined by operatives for its composition, i.e. to remove any non-polyethylene plastic film and to separate the different colours that may have been delivered. It is also examined for non-plastic contamination such as paper, labels and general waste – these are also removed prior to recycling.

- **Crumbing or shredding**

The manually separated film is then fed into a crumber, which is a high-speed set of rotating knives that divide the film into millimetre-sized flakes. This is done to homogenise the material in preparation for pelletising and to make it more convenient for handling.

- **Washing**

Washing is not always undertaken due to economic reasons. If it is deemed necessary to clean a feed washing is done once the material has been shredded, but is not usually done on crumbed film as it may cause filter blockage.

- **Melt filtering and pelletising**

The film is then heated and passed though a fine filter containing an array of laser-drilled holes that remove up to 4% contamination from the molten material. The material then passes into an extrusion assembly that produces pellets which are water-cooled and fed to a silo for inspection if necessary.

- **Preparation for manufacture**

As part of the quality control process the pelletised material is mixed with additives or virgin material as required. This depends on the application of the final product and therefore the pellets can be evaluated at this stage for properties such as melt flow index prior to moulding.

- **Masterbatching**

Masterbatching is a term given to the process of mixing a polymer feedstock with a smaller quantity of material that contains a large concentration of additives such that the final mixture has the desired properties for the product. At this stage the variety of pelletised masterbatch is mixed with the recycled pellet in a fountain blender. Further mixing is achieved during the extrusion process.

- **Extrusion**

The final mixture is then extruded in an industrial film-blowing machine. A number of extrusion lines are in operation at the plant, depending on desired thickness, colour or dimensions of the product. More specific details on film blowing can be found in Chapter 2.

### 3.8.2 Secondary recycling example – Centriforce Products ltd.

Centriforce is a plastic recycling company based in Liverpool, UK. The company specialises in producing extruded profiles and sheet material from waste polyethylene. Unlike Mercer, Centriforce produces a product that is quite dissimilar to the waste source from which it takes its feed material, therefore it is to be considered as a secondary recycling operation.

The plant functions in a similar fashion to the Mercer example, inasmuch as the material is unbaled, sorted, shredded, pelletised and finally extruded. The differences between them are that Centriforce needs to perform no washing or melt filtering because of the thickness of the extruded profiles. Relatively large amounts of contamination (in comparison to film extrusion) can be tolerated because they will not significantly affect the mechanical properties of the final product. Material property specification is maintained via masterbatching with known quantities of additives.

### 3.8.3 The Ecoplast / Erema product – a modern recycled film product.

One of the principal aims of this thesis was to evaluate the recyclability of film products. It would be logical therefore to include a recycled film product as one of the classes of material to undergo testing. A material was chosen that would be a likely candidate for a recycled film that could possibly be used in the future, should recycled film products become more widely available. This material was produced as part of a recycling trial to evaluate the feasibility of producing polyethylene film from waste material sources [10].

The film, produced partly using machines manufactured by Erema Plastic Recycling Systems, was produced in the following four stages. Firstly, the waste plastic film was procured and baled at a waste transfer station in North Wales. No attempt was made to separate or purify the material by hand at this point. Secondly the material was shipped to the Ecoplast facility in Italy where it was cleaned in water via a two-stage washing process, normally used for cleaning agricultural film. Thirdly the material was pelletised at the Erema facility, located in Austria. This process was employed to melt filter the material, i.e. to clean the plastic further by removal of contamination in the liquid state, and to agglomerate the material into pellets for ease of transportation and further manufacture. Fourthly the material was extruded and blown into a number of products (at Centriforce and Mercers, both covered earlier) the thinnest having a film thickness of 250 micron. This integrated process was a demonstration of what could be a fully-automatic manufacturing system that takes waste plastic film, cleans it to an acceptable standard and produces a new film product. Other processes do exist but they are either concerned with recycling clean feedstocks or turning contaminated feedstocks into low-value products. The complete route has not previously been applied to a waste source of such high contamination. Many of the steps used are more commonly associated with processing cleaner material but integrating all of the steps into a single process would simply be a matter of bringing the technologies together. A fuller explanation of this process and the experimental trials used to evaluate its feasibility can be found in Appendix F.

Although the mechanical properties of the mixture were known from tensile testing in a lab, its composition was not. Some compositional information was known from visual inspection of the input feedstock (waste film material) that was taken from the

MRF. Experimental testing covered in this work also aimed to identify the actual composition of this material and which specific polymer or micro-scale properties could be attributed to its mechanical properties.

X-Ray Diffraction (XRD) and Gel Permeation Chromatography (GPC) testing were arranged to discover information on the crystallinity and molecular weight distributions respectively. These tests were then compared to a Virgin LDPE and packaging grade HDPE in order to draw comparisons between the variety of grades of packaging polyethylene. This was then compared directly with the Erema product to determine which elements of its composition were responsible for it properties. Details of these experimental procedures are given in Chapter 5.

The significance of this testing is that it sets out a framework for understanding the properties of recycled plastic products based on the waste material that was taken for input. It is possible that such results can determine the general application of plastic waste even before it has been cleaned or recycled. Conversely, it can also be used to estimate the likely composition of a recycled product given some of its mechanical properties, rather than arranging expensive composition testing, saving both time and money.

This process has been the precursor to the work covered in this thesis. Although a successful project, the Erema processed product was still unknown in composition and its physical properties could not be fully attributed to any life-cycle factors. The follow-up work in this thesis was developed to more fully understand how a waste plastic film product will behave after it has been recycled, and what the actual effects of the recycling will be.

## 3.9 Tertiary recycling

Tertiary recycling is a method for reclaiming materials or energy from a variety of polymer-based products rather than using disposal. By definition it is the processing of plastics back to valuable chemicals or fuels for reuse. In the tertiary recycling process, plastic waste is converted into reusable hydrocarbon fractions for further reprocessing into polymers, monomers, fuels, or hydrocarbon-based chemicals. Generally speaking tertiary recycling is used for plastic waste streams that are too mixed or contaminated to recycle effectively.

Pyrolysis of plastic waste has been proposed as a tertiary or feedstock recycling route where the plastic waste materials are processed back to produce basic petrochemicals that can be used as feedstock to make virgin plastic or refined fuels. Previous work has examined pyrolysis of LDPE to produce feedstock chemicals consisting of a series of alkanes, alkenes and alkadienes [52]. Similar work has also been undertaken on Automobile shredder residue [53].

Tertiary recycling is an indirect method of recovering value from waste plastics. It is not currently a well recognised or employed way of recycling, mostly due to economics and quality of the final product.

## 3.10 Summary

Modern procedures for the separation and mechanical recycling of plastics, both rigid and film have been discussed. The particular method employed by the recycler to sort, clean and recycle a plastic waste feedstock is dependent on the condition of that feedstock and the application to which the final product will be used for. Higher-value applications tend to require clean and well-defined material inputs, this often involves more costly separation and cleaning processes, but this is again dependent on the quality of the feed.

Of the process routes highlighted, only primary recycling is currently used to manufacture a product that is generally recycled again. Other forms of recycling produce a product that is not normally recycled again, i.e. down-cycled. In order to produce sustainable markets in the future it is a sensible idea to avoid down-cycling wherever possible, in order to promote sustainable recycling.

The current plastic recycling industry is an established one but not used to employing material that has arisen from low-value waste sources. The challenges of cleaning contaminated feedstocks to an acceptable level whereby high value applications (such as thin films) can be employed are yet to be addressed. This highlights a need for research into how contamination and other factors encountered whilst with the consumer affect the properties of the material to be recycled.

The Ecoplast / Erema system described in this chapter is a positive start in addressing the problem of contaminated and mixed feedstocks to high-value applications. This trial process has shown that washing and melt filtering can be performed to produce a commercially acceptable film product [54]. To compliment this, a method of reliable predicting the resultant material properties of a waste feed would be desirable. Such a method should take into account the life-cycle of the product and its constituents.

# Chapter 4 – Specification of experimental investigation

## 4.1 Introduction

This chapter covers two areas of the study. Firstly, there is a literature review of relevant topics involved with modern technical aspects of plastic film recycling, including life-cycle factors such as contamination and degradation. This section also details previous research made on plastic recycling and the associated problems that have arisen from trial schemes to recycle co-mingled and contaminated feedstocks. In particular the aim of the literature review was to assemble the details of factors that inhibit plastic film recycling and highlight any areas where further research would help to quantify the problems faced by recyclers.

Secondly, there is a preliminary discussion of the experimental work specification required to meet the aims of the thesis, which are based on the factors introduced in Chapter 3. The design of the experimentation that follows was based on the 5 factors selected to be of prime significance in this chapter. This study was used to outline knowledge in plastic film recycling that were lacking key information that is required to determine feasibility.

## 4.2 Feasibility of recycling polyethylene into new products

The waste management hierarchy [24] places recycling as an important waste treatment methodology, above energy recovery and disposal, although below reduction and reuse. As previously stated, there are two major forms of mechanical recycling. Primary recycling, where the product is recycled directly into the source from which it came and secondary recycling, where a different product is made. This can often be referred to as down-cycling, if the new product is not recycled again. Currently plastic products are far more likely to be down-cycled than directly recycled [55] due to a number of factors discussed in this chapter.

Ideally, recyclable packaging plastics such as polyethylene should be recycled into new packaging products, but polymer degradation, economics, separation and contamination are factors that oppose this route. Investigations have been conducted on these factors in the past, but to date no research has covered the amalgamation of these effects in order to study the problem in its entirety. These life-cycle factors rarely operate in isolation, but studying them individually will help build a logical picture of their effects.

The effects of recycling plastic packaging are a key preliminary factor. Previous research has looked at the quality and material properties of recycled HDPE as it is recycled, including changes in crystalline properties [56]. Other work has examined the effect of producing recycled beverage containers, for example, the blow-moulding of bottles produced from 100% recycled polyethylene from different waste sources [55, 57]. HDPE samples were taken from both municipal recovery schemes and automobile shredder residue. Although the recycled HDPE was within material specifications for blow-moulding, evidence was present to suggest that the recycling process made this material become brittle.

The work concluded that recycled PE material can be used for applications other than low-quality products, provided a clean, segregated source is available. However, this work did not involve the study of any economics to prove that the process would be viable in a realistic market. Given the high purity of the input feedstock it is unlikely that such a carefully separated and cleaned product would yield profit.

Other research found that some of the expense of separation could be avoided if polymers such as LDPE and PP could be mixed together to make new products. Polypropylene is a common contaminant within polyethylene recycling feedstocks because it is used as bottle caps and adhesive packaging tapes. Toleration of small amounts of polypropylene can be achieved by the use of compatiblisers to effectively mix the two compounds together into a matrix. A compatibliser is a chemical which bonds polymers together that would not have normally reacted. The mixed materials had properties close to that of virgin materials, but the method used to combine the two was complex and in a realistic waste management situation would probably prove too complicated [58]. There would also be the problem of mixing the compatibliser in the correct ratio to the PP, which would require accurate estimation of the feedstock's composition.

Work has been carried out on the creation of matrix composite materials made from polyethylene blends with PET, both of which were recovered from post-consumer sources [59]. Thermo-mechanical recycling produced mechanical components, such as gear wheels, that had potential for use in engineering applications. The ultimate tensile strength of this material ranged from 22 to 28 MPa. It is accepted within the industry that 4% PP in PE does not adversely affect the material properties, but this again depends on the application for the recycled product [2].

## 4.3 Degradation of polymer structure and stabilisers

From an engineering perspective, it is essential to understand the degradative processes that occur during the product life-cycle and during the recycling process. Studies of plastic films suggest that for high-specification applications, such as thin films, degradation can be a significant factor in the loss of material properties, such as maximum elongation [60]. In particular, ductile polymers, such as LDPE can show brittle behaviour when the recycling is carried out on strongly photo-oxidised materials. Photo-oxidation is a process whereby polymers are oxidised under radiant energy from Ultra Violet (UV) light, this normally results in brittleness in the plastic.

Oxidative degradation is very likely when plastics are exposed to large amounts of UV radiation, which is likely if the films were previously used in agricultural applications. Such degradation can be attributed to branching, cross-linking of polymer chains and chain scission, seen as a change in mean molecular weight of the polymer, brought on by exposure to photo-oxidation and thermo-oxidation in recycling apparatus.

A potential solution to this problem is the use of stabilising chemicals to counter the effect of cross-linking of polymer chains and bonding to oxygen. Stabilising compounds can take the form of complex organic compounds such as lactones or simple inorganic fillers, like talcum [61]. The use of additives which stabilise the polymers against light, and heat from mechanical stress, may be useful to prevent degradation phenomena during processing and to extend the life-span of the materials. Research on multiple processing showed that for a number of extrusion (recycling) cycles, an appreciable increase of maximum elongation can be obtained by the adding of stabilising systems [62, 63]. This was attributed to the stabilising compound inhibiting the action of cross-linking by the polyethylene chains. Tensile strength, however, was not recovered by the stabilisers and thus some brittleness will always be unavoidable.

As for changes in the material behaviour during manufacture, work has been carried out to understand melt-flow behaviour of recycled polyethylene, which is derived from analysing changes in Molecular Weight Distribution (MWD) and Melt Flow Index (MFI) [64]. It has been shown that it can be observed that there is a decrease in

MFI when HDPE is reprocessed, indicating an increase in the viscosity and molar mass of the polymer [65]. This research also studied the action of antioxidants to limit the amount of degradation in recycled polyethylene. It found that antioxidants efficiently hinder reactions leading to chain extension and cross-linking, but they cannot stop the action of unsaturation, which leads to oxidation.

The effect of multiple processing and recycling steps of polyethylene compounds has been examined in previous work [66]. By manufacturing, testing, re-grinding and re-manufacture, a number of samples of HDPE were produced. Analyses of the changes in tensile strength, maximum elongation and melt flow index were examined. It was found that no significant change was identified in the material's rheological properties, indicating the possibility of returning these residues of HDPE to their original manufacturing processes. However, this work did not re-cycle the material more than twice, thus more work is needed in the understanding of successive recycling. The work only concentrated on one kind of polyethylene and modern packing applications use a wide variety of this material, with substantial differences in molecular weight.

Adding Linear Low Density Polyethylene (LLDPE) to LDPE has been studied in order to understand the interaction of these two similar compounds [67]. This relationship is useful because it is often used industrially to alter the rheological properties of LDPE prior to recycling [3]. LLDPE has a lower MFI than LDPE and therefore the addition of this polymer aids in the production process of recycled films. It was found that chemical modification with compatible polymers increases both viscosity and elasticity of modified LDPE and blend systems with LLDPE.

## 4.4 Contamination of recycled feedstocks

The effect of contamination on plastics recycling has received very little attention in previous research. As with the recovery of any waste material the net economics of the whole process, from initial consumer disposal, through the recovery and recycling phases, to re-marketing as a new consumer product, must be favourable or the recovery operation will not function economically. Removal of contamination has been cited [10] as causing additional costs in the recycling process, which can lead to an uneconomically feasible process.

Previous studies have shown that recycled plastic is often of inferior quality to that of virgin material [55]. Studies associated with actual material life-cycles and associated contamination have shown that gluing makes mechanical recycling less favourable owing to troublesome dismantling, and the high degree of contamination from the glue [68]. Dirt and organic food wastes can also cause problems when recycling, which should be quantified [69]. The cleaning of this contamination can have a positive effect on the feedstock for recycling, as was the case in research done on HDPE flake [70].

Some research has concentrated on the effects of mixing painted films with polypropylene for recycling, as can be the case in automobile bumpers. It was found that the paint was degrading the end product to such a degree that it was no longer within acceptable design limits. A process was therefore developed to remove the painted film and thus clean the input material to such a level that it could be used to make a usable product [71].

It has been suggested that contaminants from waste sources and degradation of the polymer chains can produce small amounts of low molecular weight hydrocarbons such as benzene compounds during recycling. Research has shown that these compounds can be generated during recycling, which could be of concern if the film is to be used for food applications, but concentrations are generally considered below dangerous limits [72].

## 4.5 Overall physical effects

Having described and discussed the potential problems associated with producing a plastic product taken from a waste stream, it is important to investigate how individual life-cycle factors act in conjunction with one another. A combined approach will be more relevant to determining the change in physical properties prior to and during recycling as it is more realistic.

Research into plastic recycling, whether rigid or film, tends only to concentrate on either specific technological problems (such as those examples highlighted in Sections 4.1 to 4.4) or waste management issues, such as diversion, best practice and economics [73, 74, 75]. To date there has been little or no research on the effects of potential and realistic life-cycles of the recyclate that combine multiple degradation effects. No data was found in the public domain that quantitatively outlined the combined degradation effects of life-cycles and recycling processes. Typical factors in the life-cycles of recycled plastics include heat cycling, dirt contamination, incompatible plastic contamination and mixing with similar feedstocks.

## 4.6 Experimental studies undertaken

Based on the information from the previous sections, the aims of the experimentation part of this work were outlined. The purpose of this work was to understand the variation in mechanical and physical properties of different types of polyethylene as they undergo processes akin to modern recycling and how different life-cycles affect their ability to be recycled. Since packaging materials are predominantly made from HDPE, LDPE and LLDPE, with most recycling centred on these materials it was decided to concentrate the experimental testing on polyethylene feedstocks.

The experiments were designed to simulate a number of potential feedstocks that polyethylene film recyclers might encounter entering a recycling plant. To achieve this, the polyethylene for the experiments was subjected to a number of simulated life-cycles in order to mimic what might have happened to it in the consumer world. These simulated life-cycles when achieved by laboratory preparation.

To quantify the effect of such factors on the plastic a series of parameters were outlined. These parameters each have an effect on the properties of the polyethylene and can result in a material that cannot be reprocessed into new film products. They were chosen based on research of waste management issues, such as the product life-cycles and the opinions of industry professionals [2, 3, 76].

It was seen as essential that the polyethylene should satisfy as many of the key parameters as possible and to be versatile in application and manufacture. In cases where the final material would only satisfy perhaps one or two key parameters, alternative products could be made from it, but then doubts would be raised over the economic viability of the final recycled product once it had been processed into the new specification.

The five key parameters that determined the specification of the experiments are outlined in 4.6.1 to 4.6.5.

### 4.6.1 Effect of processing the plastic into its into original product

As discussed in Chapters 2 and 3, the plastic product starts life as a polymer and is manufactured into the desired shape using heat and chemical processes. This can involve problems such as thermal-oxidative degradation and also more complicated factors. Given that some modern packaging products require processes that are complex in nature, it is essential to understand whether the original manufacturing can effect the recyclability of the product itself. Examples may include cases where the polymer is bonded to other non-compatible polymers or if cross-linking additives are used that may cause the polymer to become more like a thermoset and not be applicable for re-processing. Stabilising compounds or stiffeners, such as chalk, may be added prior to manufacture.

### 4.6.2 Effect of inks and dyes used in labelling

Labelling compounds are generally made from pigments that are unlike the polymer they are being used with and thus their mechanical properties will be inherently different to the polymer they are suspended in. From a manufacturing stance, pigments are usually more viscous than molten plastic and will therefore impede some forms of mechanical recycling. Heavily dyed products, particularly packaging film, as the dye/polymer ratio is usually high, are less likely to retain their original mechanical properties because of the dye substances making weaknesses in the remanufactured product. Applications such as carrier bags can be heavily dyed and it should be understood how much of an effect these compounds have on the recyclability of the polyethylene itself. This presents the risk of unmixed regions or clumps of dye material causing localised weaknesses through the material. Effective mixing will also be a factor in producing a consistent product and should be considered when looking at dyed feedstocks.

### 4.6.3 Effect of mixing with other packaging materials

Many modern packaging products are tailored to meet a specification and this often results in the polyethylene being bonded to other substances, some of which can be polyethylene based (as in the case of all-plastic food packaging such as meat trays) and some of which are not (as in the case of cardboard/plastic composites such as Tetra-Pak ™). The effect of contamination via similar plastic products would be useful in understanding if certain types of contamination could be tolerated and at what levels these may be.

Practical scenarios encountered during the recovery phase, for example incorrectly sorted materials from a MRF source may give rise to a mixture of polymer types being delivered to the recycler. Plastic materials such as polyethylene and polypropylene can be mixed together due to their similar appearance [77]. PVC is a material that is receiving increased attention in the recycling community due to health and safety risks as well as the damage it can cause to moulding equipment [78].

### 4.6.4 Effect of successive heating and cooling (e.g. recycling) cycles

The cycling effect of successive processing has been given some attention in literature [79], but has generally concentrated on the recycling of rigid products such as bottles and crates. No work was found that covered thin membranes such as LDPE or HDPE films and this should be understood if plastic film recycling is to become more popular. Understanding whether the material becomes degraded or less easily manufactured after a number of life-cycles is important because recyclers will need to understand if there is a finite number of recycling cycles a polymer can survive before its properties fall below a minimum material specification. Rheological properties will again be most important here as adverse changes to the MFI will make the recycled material impossible to manufacture. It will also be useful in trying to understand how much degradation takes place per heat process in order to estimate the resulting material properties of a mixture before it is recycled.

### 4.6.5 Effect of contamination from materials encountered during the product life-cycle

The actual environment which the product goes through, including the recovery process leading up to recycling will expose it to contamination. This can be from the product which the polyethylene encloses itself (e.g. food), dirt from its surrounding environment or from cross-contamination with other waste products. By subjecting the polyethylene to simulated dirt, the effect of such contamination can be quantified. It will be important to understand if any changes in physical properties are attributed to changes on a molecular level or from contaminants impeding the structure on a larger scale, i.e. creating small holes in the product. Molecular-level tests will determine whether or not the contamination effects the polymers themselves or simply causes discontinuities in the material structure.

## 4.7 Properties examined in this study

In order to quantify the effect that the previously mentioned life-cycle factors have on the properties of the material, inasmuch as whether the polyethylene would have any viable applications, a series of tests were chosen. These tests were designed to show how the material properties of the material changes with increasing amounts of life-cycle factor (e.g. heat cycling or dirt contamination). Ultimately these tests would then be used to determine whether the environments to which the plastic had been exposed to would result in an unprofitable recycled product. Five major physical properties were chosen, each with a particular relevance, explained in more detail in sections 4.7.1 to 4.7.5.

### 4.7.1 Tensile strength

Tensile strength was chosen as it is an indicator of how the stiffness of the plastic materials had weakened or improved during the product life-cycle. Measurement of this change was achieved by finding the Ultimate Tensile Strength (UTS) of the plastic compound in question before and after the simulated life-cycle was imposed on a test sample. Standards exist for the tensile testing of plastic films, which can be employed for the experiments required herein.

Examples of expected changes would be chain scission or shortening that may occur during some heating processes, which will cause the polyethylene to become brittle. Such brittleness can be seen as an increase in the tensile strength of the polymer. Other material property changes can arise from contaminants such as fillers and dirt that may cause an increase in tensile strength, but the quantitative effect of contamination via materials typically exposed to polyethylene film over its life span have yet to be studied.

### 4.7.2 Elongation and fracture under tensile load

Maximum elongation under tensile load of the test specimens was also examined. This test was deemed significant because changes in ductility will substantially effect the applications of the polymer product. Most plastic film applications require excellent flexibility and ductility under strain, as well as strength under load. Should brittleness result from film recycling, potential applications would be limited, which could exclude recycling the film directly into new film products.

Understanding how factors encountered in the products life-cycle and recycling process is paramount in selecting potential markets for the reprocessed film. It is therefore essential to understand how such life-cycle factors affect the ductility of the material, since most plastic film products are used because of their ductile properties. Thus, measuring the elongation at maximum load was a key test parameter in this work.

### 4.7.3 Melt Flow Index (MFI)

MFI is a measure of how easily a material can be drawn out, moulded or blown into profiles during manufacture. The lower the MFI, the more easily a polymer can be made into thin film, which is the more profitable of the applications for manufactured plastic products. As with any material, the thinner the film, the more product that can be made per unit mass and the therefore the more profit that can be generated for the same material cost.

Knowing how life-cycle conditions affect the MFI of a polymer was deemed important because the aim of this investigation was to understand the degree of which recycled polyethylene film is commercially saleable. Quantification of how life-cycle factors influence the MFI of a polymer compound was deemed important in order to determine how many heat cycles or how much dirt contamination was tolerable for a particular application. Since the MFI is a factor which determines how effectively film can be blown, understanding how it is affected by the life-cycle of a polymer product is key in deciding on whether recycled film products are worth producing, from an economic point of view. Film blowing operations are principally interested in MFI as it is production issues that are most important [3].

Typical values, under type "D" of the MFI standard as is normally used with packaging polyethylenes, are in the region of 0.5 to 2.0 g/10 min.

### 4.7.4 Polymer crystallinity

Polymer crystallinity is a property that determines many of the physical properties of a polymer, for example UTS and MFI, as discussed in Chapter 2. It was seen as essential to have quantitative information on the crystal structure of the polymers as they were recycled. The effect of contamination on the micro-structure of the polymers was also seen as useful because it should be able to determine whether the contamination was damaging the polymers themselves or simply causing localised weaknesses in the structure of the moulded part.

Evaluation of crystallinity would also provide information on whether the life-cycle effects had caused the crystal spacing of the polymers to change, which will aid understanding of the causes of polymer degradation. Physical properties such as UTS and MFI do not necessarily explain why the polyethylene test pieces have altered due to life-cycle factors, but molecular scale properties such as crystallinity will give an insight into these factors.

### 4.7.5 Polymer chain molecular weight

The condition of the polymer chains themselves are an essential piece of information on deciding how the polyethylene test-piece had been changed over the simulated life-cycle. Changes in mean molecular weight or polydispersity index will aid in the understanding of how the life-span of a plastic product effects the polymer chains from which the products are manufactured. Chain shortening usually produces brittle plastics, which severely narrow the potential applications. It would therefore be helpful to evaluate the degree to which the polymer chains are affected after the plastic has been exposed to contamination or successive heating and cooling cycles. Contamination effects on both an inter and intra polymer chain scale will affect the molecular weight of the polymer chains and the plastic as a whole. As such these effects must be understood in order to determine acceptable contamination levels and life-cycles for potentially recyclable polyethylene film products.

## 4.8 Outline specification and preparation of samples

To meet the requirements laid down in the previous section, four classes of life-cycle factors were designed. Each class was assigned a specific variable that was the contributing aspect of the life-cycle factor, for example number of heat cycles or percentage contamination by mass. Relationships between the variable and material properties were then measured experimentally. The effects in terms of change in physical and molecular properties were analysed and can be found later in Chapter 6. Each class of material was subjected to the experimental tests discussed in section 4.7, namely tensile strength, maximum elongation, melt flow index, evaluation of crystallinity and evaluation of molecular weight. Where it was not deemed necessary (because there was no appreciable change in crystallinity) the more costly chromatography (GPC) measurements were not performed for financial reasons.

### 4.8.1 Successive cycling of material

This test was aimed at determining the change in mechanical properties as the polymer was heat cycled a number of times. The polymer mix was injection moulded into a number of test pieces, as shown in section 5.2, some of which were tested to examine the physical properties, some were retained. The retained pieces were then re-ground and re-moulded ready to form the next batch as shown in Figure 4.1. This process was repeated a number of times in order to simulate a successive recycling process, such that the relationship between the polyethylene sample's physical properties and number of heat processing cycles was examined.

Natural wastage, such as incorrectly formed test pieces, scrap and mould flash meant that the equivalent of 10-12 test pieces were consumed each cycle, although only 7 were required for experimentation. Six test pieces were used for mechanical testing and one piece was retained in an archive for future testing should the need to re-examine a batch were to arise. The retained pieces were shredded using a Fellowes

PS70-2CD in-line document shredder, using multiple passes to cut the test pieces into 5mm square fragments, similar in size to the pellets that constituted the original virgin material.

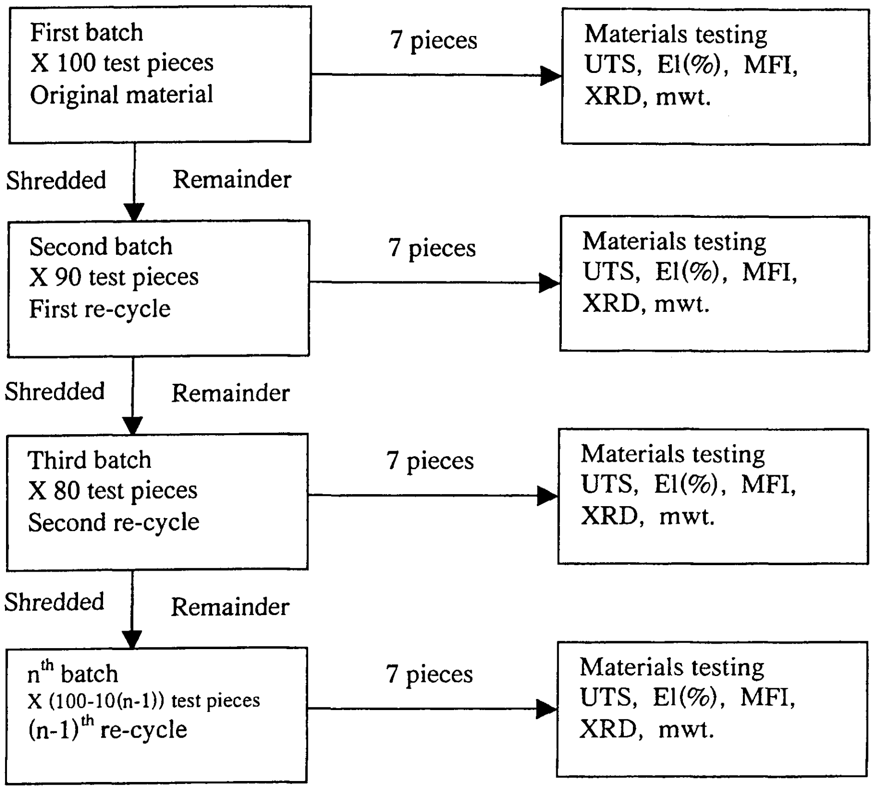


Figure 4.1 schematic of successive recycling experiment.

The input materials used for the experiment were:

- Virgin LDPE, i.e. un-moulded polymer from Dow Chemicals Ltd.
- A modern recycled film product (known as the Ecoplast/Erema Product), see Section 3.8.3.
- Used HDPE supermarket bags
- Used retail packaging film from a local supermarket.

### 4.8.2 Contamination effects

This test was aimed at determining the change in mechanical properties as the polymer was mixed with a known non-plastic element. A filler, in this case talcum powder, which is often used to stiffen polyethylene, was used to simulate the effect of dirt and dust on the plastic. The concentration of the contaminant was varied from 0% to 15% and the material was tested for each level of contamination. This is outlined schematically in Figure 4.2.

The talcum was introduced to the polymer before production of the test pieces and agitated to ensure an even distribution. Mixing was performed in a dry environment to avoid cohesion of the talcum. The talcum / polymer mixture was allowed to stand in its molten state for two minutes prior to injection to aid in giving an even distribution of the talcum though the molten polymer.

The materials used for this test were virgin LDPE and the Erema extruded product.

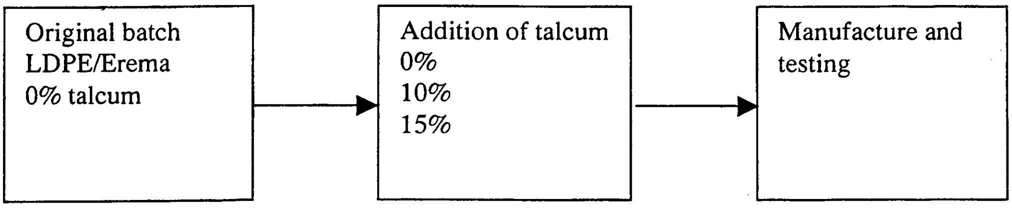


Figure 4.2 Schematic of the process by which talcum was added to the polymer at tested.

### 4.8.3 Type of contamination

This test was aimed at determining the change in material properties as the polymer was mixed with varying amounts of different types of plastic contamination. Of particular interest was PVC, PP and cellulose contamination, as they can often be found as a variety of packaging tapes in recovered LDPE film. The relationship between the physical properties of the mixture and the contaminant type was examined. XRD tests were used to examine if the polymers present in the tapes had changed the polyethylene structures or merely arranged amongst them. The polyethylene feedstocks and contaminants used are shown as an experimental matrix of parameters in Table 4.1.

Table 4.1 Experimental matrix of parameters varied whilst testing for contamination type

| Input Material | Contamination type | | | | |
|---|---|---|---|---|---|
| | Talcum | Polypropylene tape | PVC tape | Cellulose tape | Other Polyethylenes |
| Virgin LDPE | | | | | |
| Erema extruded product | | | | | |
| Post-use commercial packaging | | | | | |

The contaminant was shredded prior to mixing, as would be the case in a recycling plant. Addition of the contaminant was done independently of sample injection, prior to the sample entering the moulding apparatus. This was done to ensure even mixing of the sample and contaminant. The mixture was then allowed to settle under heated conditions for two minutes prior to injection in order to allow an even distribution of the two fractions. Figure 4.3 shows this process schematically.

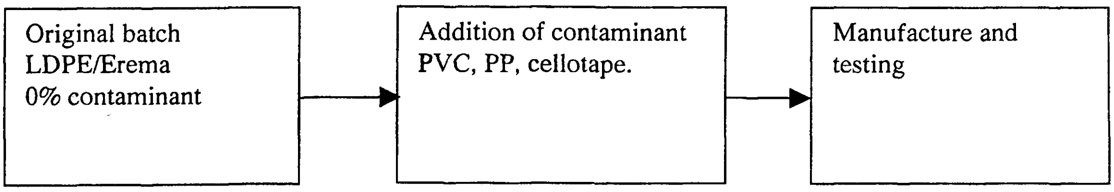


Figure 4.3 Mixing of the contaminant with the polymer sample.

### 4.8.4 LLDPE ratio and alloying effects

This test was aimed at determining the change in mechanical properties as the polyethylene was mixed with a fraction of linear low density polythene (LLDPE), which is also known as cling film. This test is of importance where mixed streams of LDPE and LLDPE are to be used in recycling applications. The relationship between mechanical properties and LDPE/LLDPE ratio was examined.

In some recycling activities LLDPE is added to LDPE in order to make the material more ductile. This mixing process was observed in a number of facilities during industrial practice, as shown in Sections 3.8.1 and 3.8.2. Understanding how the ratio affects the ductility as a general parameter is not available in public literature and would be a useful relationship to polyethylene recyclers. The results from this test were used to quantify this relationship.

Although the basis of this test was originally to study the mixing of LDPE to LLDPE it was determined that in an industrial recycling context polymer types are often mixed in order to tailor the input stream to a desired MFI. A further test was performed where two polyethylenes with a large difference in their MFI were mixed to evaluate the physical properties of different mixture ratios.

The polymer were mixed before production of the test pieces and agitated to ensure an even distribution. The mixture was allowed to stand in its molten state for two minutes prior to injection to aid in giving an even distribution of the LLDPE through the molten mixture. It was important that there was an even mixture between the two polymers as in the case of the LDPE / LLDPE mix, the two fractions were of similar colouration and determining their mixedness was difficult. The preparation process is shown schematically in Figure 4.4.

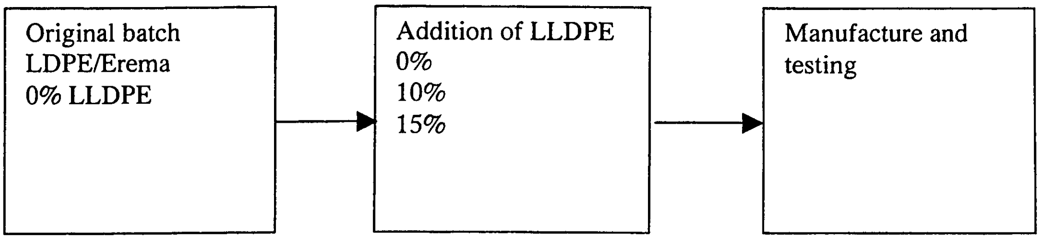


Figure 4.4 Schematic of PE alloying process.

## 4.9 Summary

This chapter has examined previous research and development work undertaken in the field of plastic recycling. It has also used the information gathered about recycling research in order to draw on areas where more work is needed, which has produced an outline a specification for the experimental portion of this thesis. The general requirements of this experimental work have been outlined and will be shown in detail in the next chapter.

According to the previous research studied, degradation caused by elements of the life-cycle of a plastic product can have a marked effect on the physical properties of the recycled product, but this is dependent on the conditions that the product was exposed to. Although there has been some relevant investigation done in isolation, there is a definite lack of research into the cumulative effect of these factors. The experimental work outlined for this research will also study the effect of these factors in combination with one another.

It is essential that the experimental research maintains a strong emphasis on industrial relevance, as the aim of the study was to determine how life-cycle factors influence the recyclability of recovered films. This is the reason why process dependent factors (principally melt flow index) should be regarded with importance. Product specifications are set by the producers that manufacture the recycled product, so the importance of production specifications is highest.

# Chapter 5 - Experimental methodology

## 5.1 Introduction

This chapter outlines the experimental procedures used to acquire data in compliance with the specification laid down previously. Detailed methods are shown to illustrate how the plastic materials were treated in order to measure their mechanical, rheological, morphological and chemical properties. This also includes how the samples were prepared, such as injection moulding and shredding. Procedures shown in this methodology were carried out in the order which they are resented, i.e. starting with injection moulding and ending with Gel Permeation Chromatography (GPC) analysis. Where appropriate, further experimental details and testing standards such as BS and ISO specifications are referred to and can be found in Appendix G. The results of these experimental tests are presented and discussed in Chapter 6.

## 5.2 Test piece manufacture

For tensile testing of plastic film material, the accepted standard is EN ISO 527-1. In order to meet this standard, test specimens must first be produced to predetermined dimensions. The dimensions of such specimens were used to manufacture a mould that could be used in conjunction with an injection moulding machine. A stainless steel mould was produced to injection mould the appropriately shaped test pieces. This two-part mould allowed injection of a molten polymer charge and easy disassembly such that the cooled plastic specimen could be removed. It was also fitted with a separate G-clamp to ensure that the two halves of the mould would not be forced apart under the pressure of the injection process. An air outlet was also machined into the mould to allow air to escape whilst the cavity filled with molten plastic.

The equipment used in the manufacture of the plastic specimens was a Fox and Offord "Polylab" Universal injection moulding machine, which is outlined schematically in Figure 5.1 and shown as a photograph in Figure 5.2. The machine briefly comprised of a handle to pump hydraulic fluid into a chamber that drove a ram, which in turn forced the polymer feed through a heated cylinder and into the mould. The machine was capable of heating the polymer charge to 300°C and delivering moulding pressures of up to 2500 psi. As the material used for the experiments was predominantly polyethylene based, the moulding conditions were set in the range of 180°C to 190°C and 1500 psi moulding pressure. These conditions were referenced from the user manual, which contained recommended operation conditions for a range of polymers.

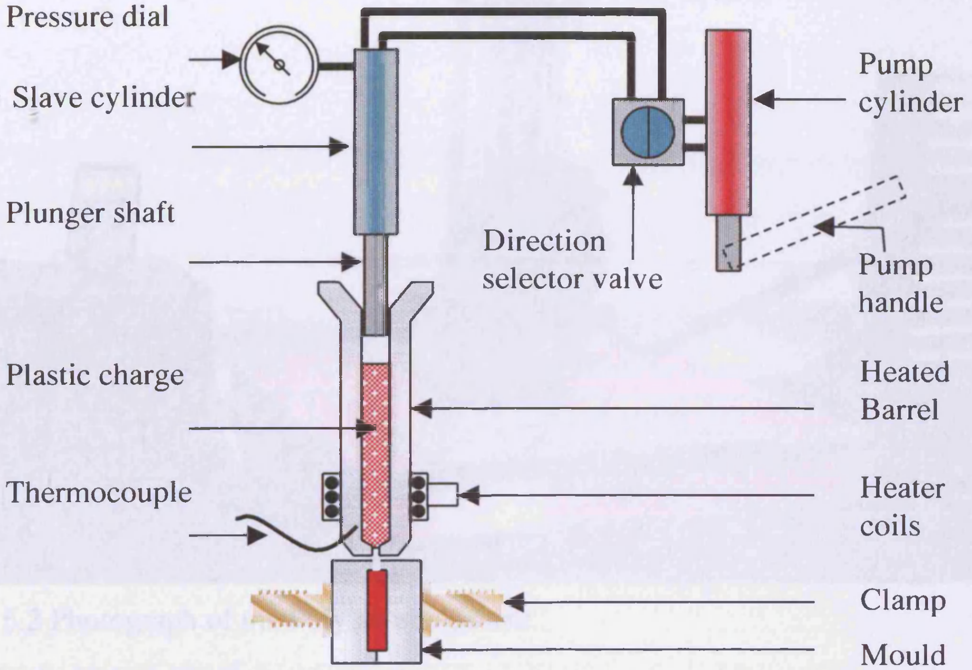


Figure 5.1 Schematic diagram of the operation of the injection moulding apparatus.

Polymer feedstock was fed into the top of the heated barrel via a funnel and pushed into place using tongs. The plastic was given five minutes to warm up under a small amount of pressure to help densify the charge. As per the operating procedure written for the device, the plastic was pumped briskly into the mould and held for ten seconds under positive pressure to allow air bubbles to precipitate from the cooling test piece. The ram was then set to run in an upward direction, i.e. to relieve pressure on the mould, to reset the system ready for the next piece. More charge was added as required.

An excess of moulded test pieces were manufactured in order to select specimens that were free from contamination and air bubbles. The six most suitable test pieces were then measured for cross-sectional area with a micrometer, with multiple measurements being used to test for discontinuities in the cross-sectional area of the piece.

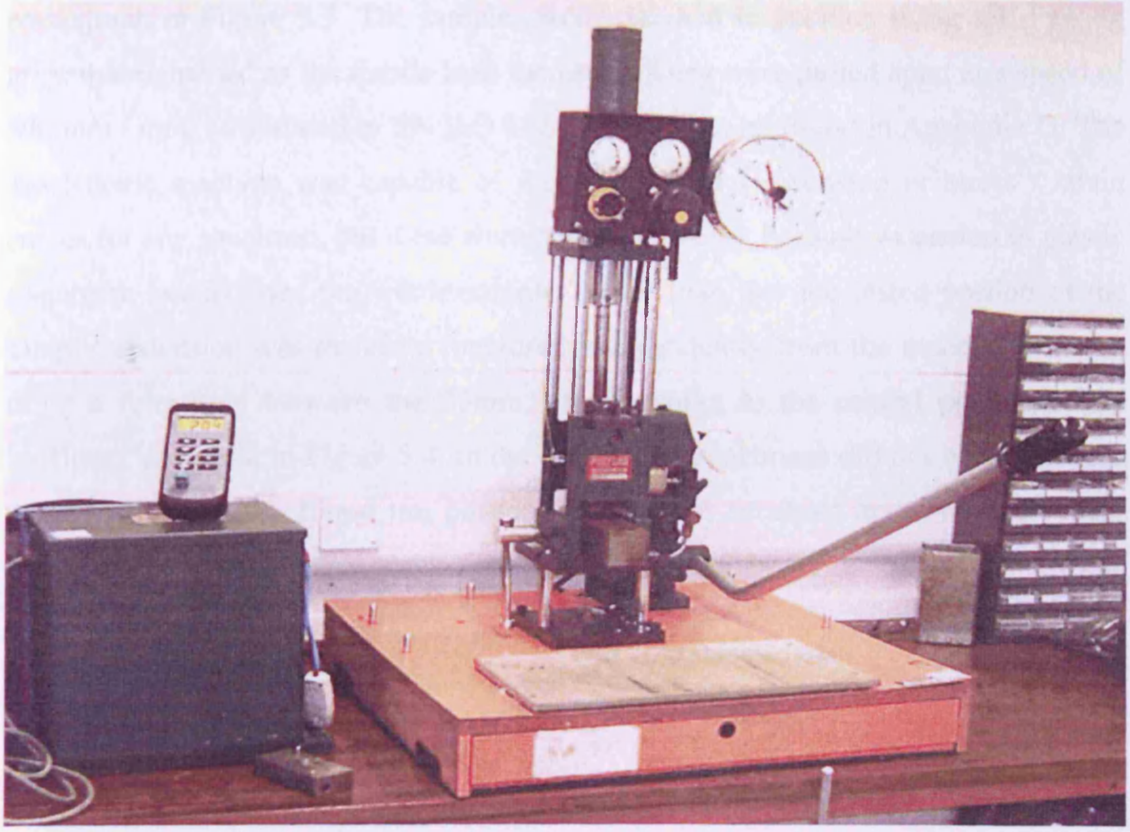


Figure 5.2 Photograph of the Polylab equipment

The specimens were then marked with test lines 25mm apart over the portion of the material that was due for testing and where fracture would occur. These lines were used to measure the extension of the piece during tensile testing. A photograph of a typical moulded specimen is shown in Figure 5.3.

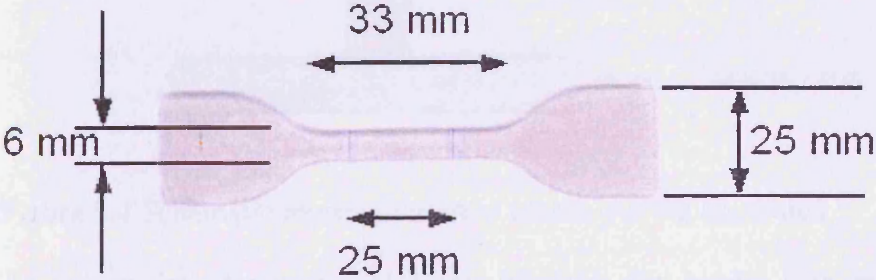


Figure 5.3 Photograph of a typical test specimen

The specimen thickness (into the page) is around 2.0 mm. The indicator lines spaced at 25mm can be seen in the photo as vertical blue marks.

## 5.3 Tensile testing

The test pieces were evaluated for tensile properties using a Testometric M500-50 series tensile testing machine, as shown schematically in Figure 5.4 and as a photograph in Figure 5.5. The samples were clamped in position using self-locking grips that tightened as the tensile load increased. They were pulled apart at a speed of 500 mm / min, as outlined in EN ISO 527-1, which can be found in Appendix G. The Testometric machine was capable of displaying load / extension or stress / strain curves for any specimen, but these were not used directly because extension of plastic specimens occurs over the whole sample, rather than just the tested portion of the sample. Extension was therefore measured independently from the machine's output using a ruler held between the 25mm spaced marks in the central portion of the specimen, as shown in Figure 5.4. In the case where specimens did not break between the lines marking the 25mm test portion, the test was scrapped and a new test piece was used, but this happened very infrequently.

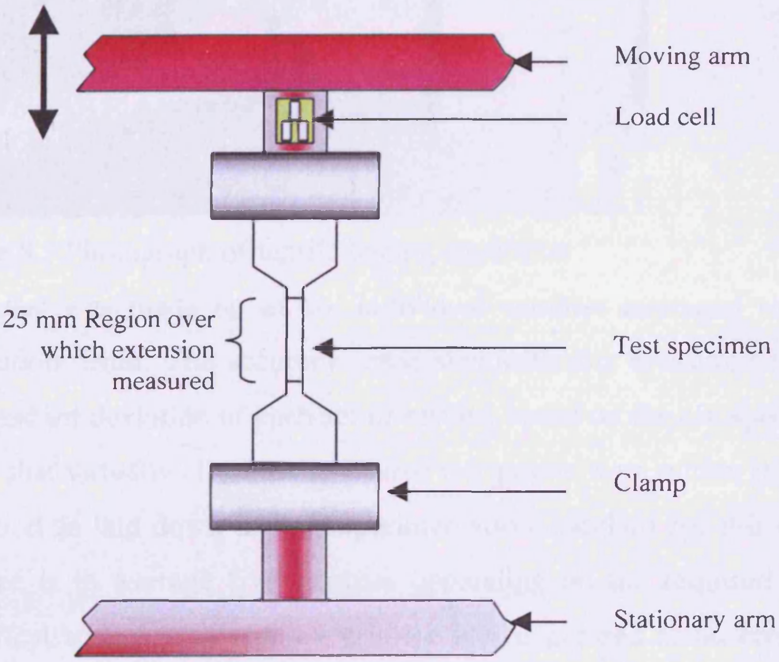


Figure 5.4 Schematic representation of tensile testing apparatus

At failure the maximum extension between the marks was recorded. Maximum breaking load was recorded using the output from the machine. The results of this experiment were entered in a spreadsheet and the data, i.e. maximum extension as a percentage and ultimate tensile strength were calculated, based on the original measured dimensions of the specimen. The tested samples and spares were retained for further evaluation or repeat testing, should the need arise for verification.

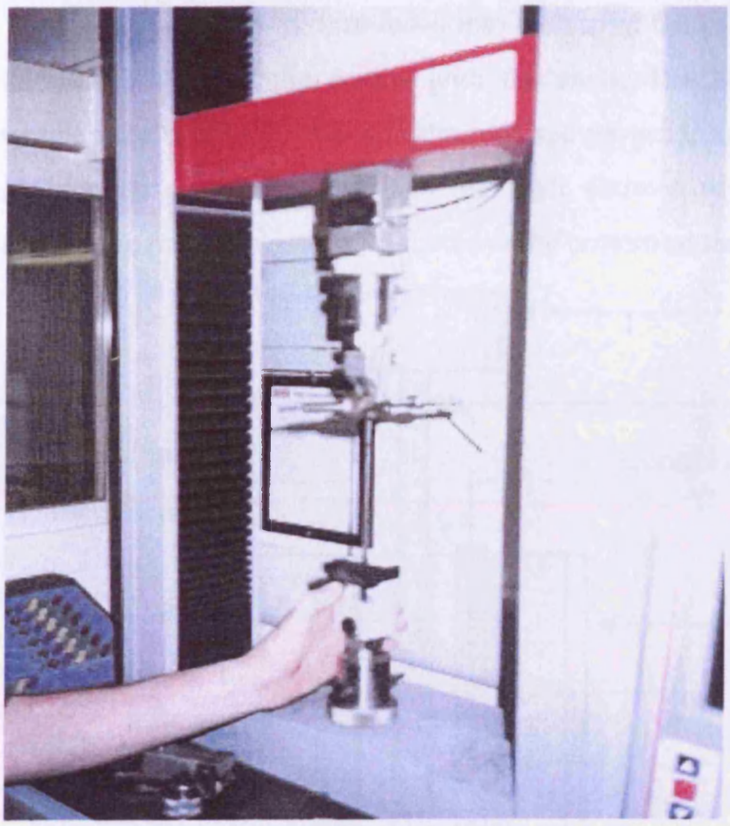


Figure 5.5 Photograph of tensile testing apparatus

Each test was made up of six individual samples averaged to give the UTS and elongation result. The accuracy associated with this measurement was expressed as the standard deviation of each set of results, based on the six specimens tested. It was found that virtually all of the measured test points were within the allowable standard deviation as laid down in the experimentation standard for this experiment. General practice is to average five samples depending on the required precision [10]. The numerical accuracy for this experiment was expressed as an error bar on the results graph, which can be seen in Chapter 6. For individual test sample results and dimensions see Appendix H.

## 5.4 Measurement of Melt Flow Index (MFI)

A device capable of measuring the melt viscosity, or melt flow index, of polymer was employed to conform to EN ISO 1133. The melt flow indexer is shown schematically in Figure 5.6 and as a photograph in Figure 5.7. This device was constructed in – house using the design criteria and specifications outlined in the standard. Conditions for the testing of polyethylene samples is nominally 190°C under a load of 2.16 kg, which is method “D” of the standard.

The plastic sample was introduced into the top of the barrel with a funnel and pushed into the bottom of the device with the shaft. The barrel was heated to the test temperature of 190°C. When at the required temperature the 2.16 kg load was put in position on top of the shaft and the shaft allowed to descend under gravity, thus forcing the molten plastic out of a die at the bottom of the barrel.

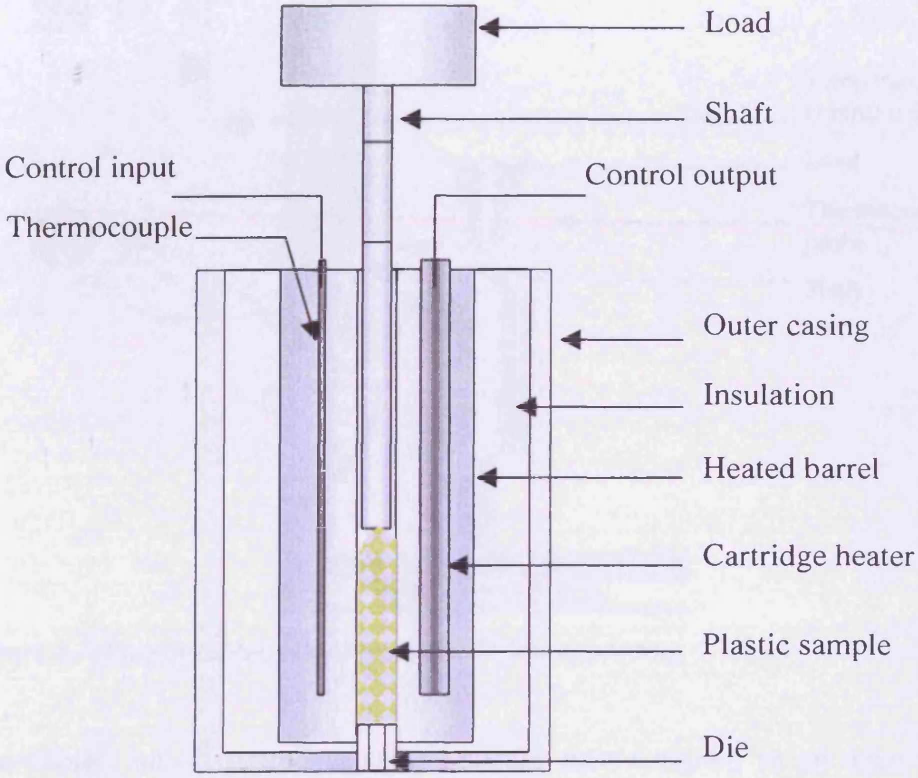


Figure 5.6 Schematic representation of the melt flow index apparatus

Temperature was measured using a 'K' type thermocouple and control was maintained by a Proportional Integral Differential (PID) control system via a Watlow series 93 microprocessor unit. This controlled the current sent via a relay to three 500W cartridge heaters, which were arranged in a parallel electrical circuit. These heaters were sunk into the barrel in such a way as to maximise an even temperature distribution. The force imparted by the load along with the high barrel temperature caused the plastic sample to flow through the die and out of the apparatus. The shaft was marked with two reference points as shown in Figure 5.6.

The shaft was allowed to descend until the first reference point reached the top of the barrel. The molten plastic flux emitting from the die was cut off, marking the start of the test and a stopwatch timer was started. The plastic flux was then cut away at a specific time interval, nominally 1 minute, and placed in a vessel. This was performed until the test had lasted for 10 minutes, whereupon the last molten piece was cut from the die and the timer was stopped. The apparatus was then purged until empty, ready for the next sample to be injected. At the start of each new test the barrel and shaft were cleaned in order to remove any contamination build-up on the walls of the components.

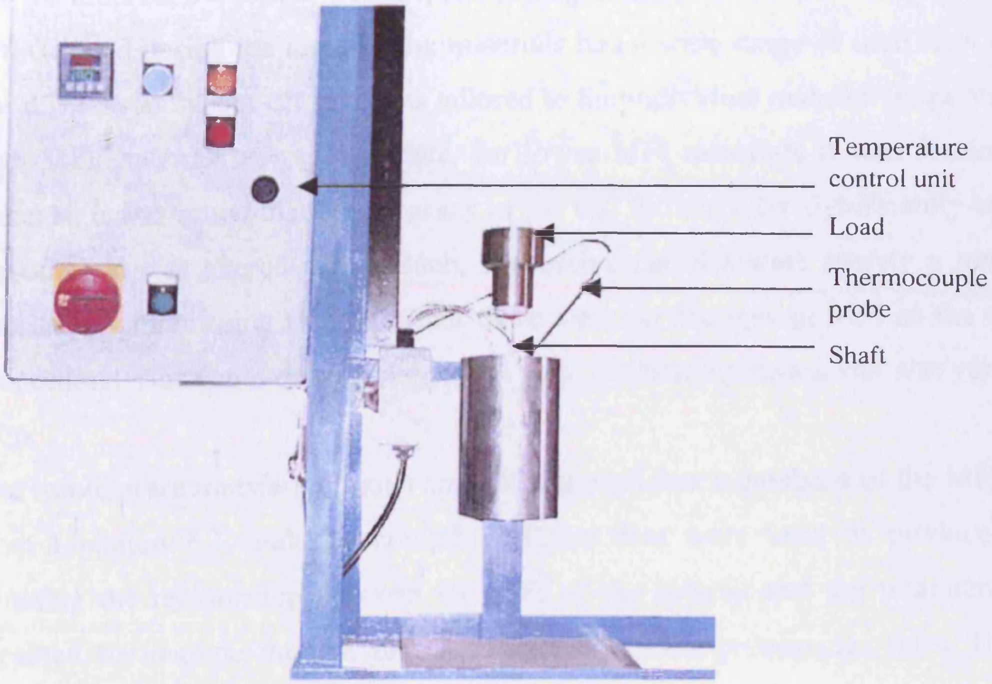


Figure 5.7 Photograph of the melt flow index apparatus

The cooled cut-off extrudate samples were then weighed to an accuracy of 0.01g using an electronic balance. They were examined to ensure if their standard deviation was within 5%, otherwise the test was re-run. The total mass extruded over the ten minutes was taken, along with the test temperature. These values were then used to calculate the melt flow index from Equation 5.1, taken from EN ISO 1133.

$$MFI(\theta_t, m_{nom}) = \frac{t_{ref} \cdot m}{t} \qquad \text{Equation 5.1}$$

where

| | | |
|---|---|---|
| $\theta_t$ | is the test temperature (°C) | [190°C] |
| $m_{nom}$ | is the nominal load (kg) | [2.16 kg] |
| $m$ | is the average mass of the cut-offs (g) | |
| $t_{ref}$ | is the reference time (minutes) | [10 minutes] |
| $t$ | is the cut-off time interval (minutes) | |

Thus, the calculation was simplified to:

$$MFI(190, 2.16) = \frac{10 \cdot m}{t} \qquad \text{Equation 5.2}$$

and the units for the results were expressed as g/10min.

It was found during the test that the materials had a wide range of melt flow indices. For this reason the cut-off time was tailored to the individual material in question. For high MFI materials it was 1 minute, for lower MFI materials it was 3 minutes 20 seconds. It was found that the accuracy of the test did not alter significantly when the cut-off time was altered and as such, successive cut-offs were merely a method of consistency monitoring to ensure that there were no changes in MFI as the test was proceeding. This could occur if a material were not homogeneous, but was very rarely seen.

The results were transferred into a spreadsheet such that a database of the MFI values from Equation 5.2 could be compiled. These data were used to produce graphs denoting the relationship between the MFI of the sample and the treatment it had received, for example the change in MFI with successive processing cycles. The MFIs were also compared to the other measured properties to see if there was any correlation between melt viscosity and other physical properties.

As per the recommendations laid out in the standard, the errors associated with this experiment are assumed to be less than 5% of reading. This was seen as acceptable for the purpose of this research and for this reason all data was assumed to have an accuracy of ± 5%. Consistency checks made during extrusion found that the mass flow rate and subsequent MFI did not vary by any more than 5% of reading during any single test.

## 5.5 X-Ray Diffraction (XRD)

The use and application of XRD analysis including a theoretical introduction to its operation is introduced in Chapter 2. For this experiment XRD analysis was carried out using a Philips PW 1710 Automated Powder Diffractometer (APD). This apparatus used Copper K $\alpha$ radiation, set at 35kV and 40 mA. The software used to operate the machine was PW1877APD version 3.6, which was run on a PC for simultaneous traverse control, data collection and storage [80].

The samples were introduced into the diffractometer and fastened in place using the existing positioning assembly. The diffractometer normally accepted glass slides around 3mm thick for powder analysis. In the case of the polymer samples, the pre-formed test-pieces that had previously been used in the tensile testing experiments were of similar thickness and could be held in place with the existing positioning clips. This was possible once they had been trimmed to the same size as the glass slides normally used, approximately 25mm x 25mm.

Figure 5.8 shows a photograph of the apparatus. The chamber containing the X-ray source can be seen at the far left of the figure; the traversing detector, which swept in an anti-clockwise direction is to the right. Samples were positioned inside the circular chamber in the centre of the image. The system was safety-interlocked controlled by the sample chamber cover.

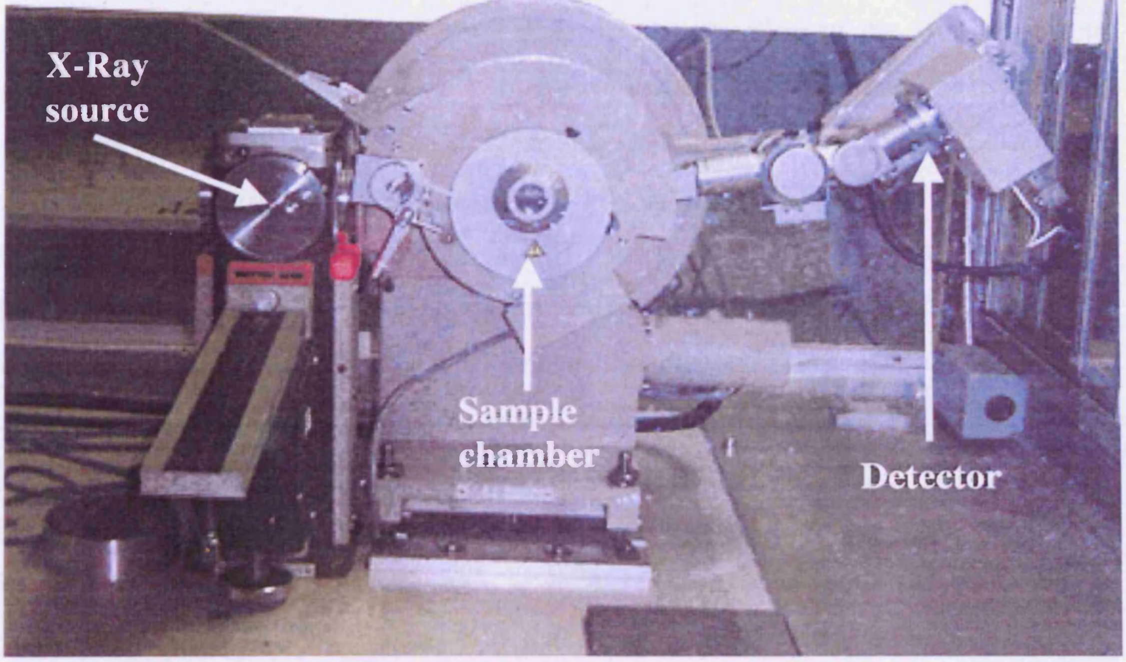


Figure 5.8 Photograph of XRD apparatus.

The apparatus was set to traverse and gather diffraction data from 3 to 60 degrees. An initial scan of wider diffraction angles with a variety of polyethylene samples showed that there was no useful data outside of this interval and thus data above 60° or below 3° was not collected to save traverse times and data file size. Each scan was taken in 356 discrete steps (i.e. 0.16 degrees of detector angle per step) with 8 measurements being taken per step, which were averaged for consistency.

At the completion of each scan the traverse mechanism was reset and the test piece changed. The results data were stored on the controller – logger PC and the software was reset ready for the next traverse. Each scan and set-up took around 30 minutes to complete, allowing for about 12 scans in one day.

The results were then exported from the logger PC in ASCII format and loaded into a spreadsheet package. The graphs of the data were examined for consistency and evaluated to see if there were any changes between successive traces as the material properties were changed from one sample to the next. Initially these results were too similar to discern quantitative changes in crystallinity and it was decided to calculate the crystallinity based on a recognised method as shown in the next section [81].

## 5.6 Crystallinity content calculation

The purpose of this computation method was to express the crystallinity of a semi-crystalline substance by quantifying the ratio of crystalline material present in the substance as a whole. This measurement involved estimation of the area under the amorphous halo which was seen as a 'hump' in the XRD pattern, and the estimation of the area under the crystalline peaks. Semi-crystalline polymer morphology in terms of polymer microstructure is explained more fully in Chapter 2.

Before the XRD trace was analysed it was treated to remove Compton scattering. Organic materials display a strong Compton background which must be subtracted from the data. Compton scattering is defined as the scattering of photons from a charged particle and it can be a particular problem when taking XRD measurements from plastic samples [82].

Removal of this scattering effect was done by studying the individual data sets to look for the background levels in the traces, as shown in Figure 5.9. This can be seen as a background level of around 50 counts at detector angles above 45° in Figure 5.9. The level of Compton scattering was unique to each data set therefore each set was evaluated separately and the Compton value read from the trace.

In order to accurately express crystallinity, intensity must be expressed in a recognised form rather than just in numerical form as an occurrence in counts arriving at a detector, which was the format for the XRD apparatus used. The intensity, i.e. detector counts, in numerical form was multiplied by the inverse of the angular dependent terms. The diffraction angle $(2\theta)$ was converted to intensity using Equation 5.3.

$$q = \frac{4\pi}{\lambda}\sin\theta \,.$$ Equation 5.3

Where q = Intensity

$\lambda$ = Wavelength of X-Ray radiation

$\theta$ = ½ detector angle

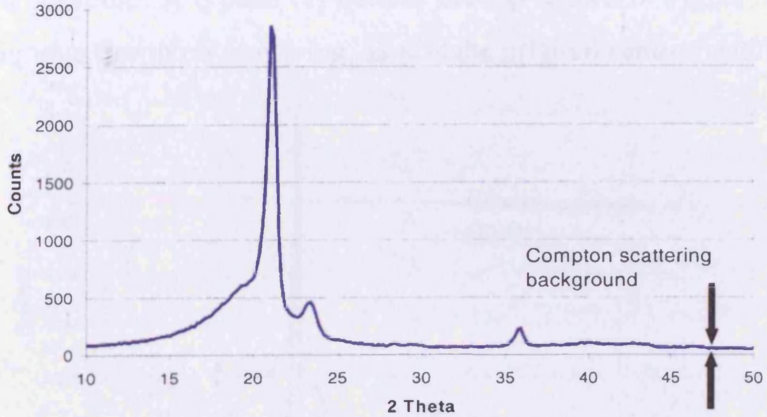


Figure 5.9 Compton scattering seen on a typical data set.

The Compton background was estimated from the raw data as the high-q value for intensity as stated above. The degree of crystallinity was then estimated from the weight of the calculated crystalline peaks divided by the sum of the weights of the amorphous background and the crystalline peaks. To determine the crystalline content of the samples the following calculations were used. The original crystallinity data was loaded into a spreadsheet and treated stepwise as per the method given below.

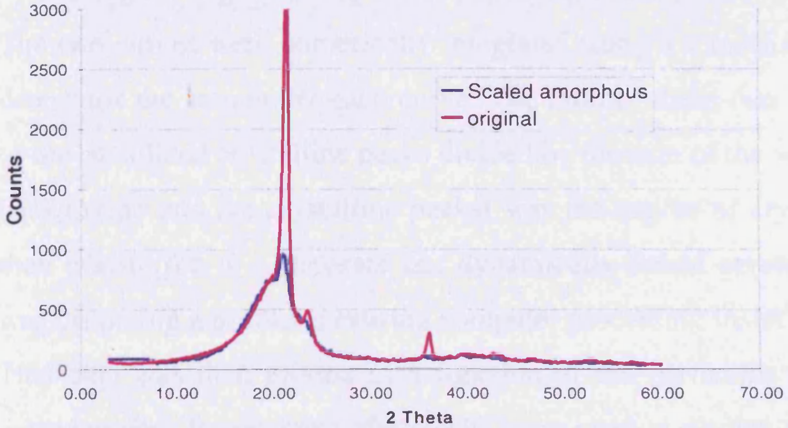


Figure 5.10 Scaled amorphous curve being matched to a typical data set

A data set was taken that had been acquired using an amorphous polyethylene, i.e. one with almost no crystallinity. For this experiment a predetermined XRD trace was taken from an expert reference source of “Exact 4001” a wholly amorphous type of polyethylene that has virtually zero crystalline content [81]. This data set was then scaled to match the amorphous part of the results curve, as shown in Figure 5.10.

The scaled amorphous curve was then subtracted from the XRD result in question in order to leave a trace that was the result of only the crystalline content of the material in question. A typical crystalline trace is shown in Figure 5.11. This was factored to remove Compton scattering, as was the original semi-crystalline data set.

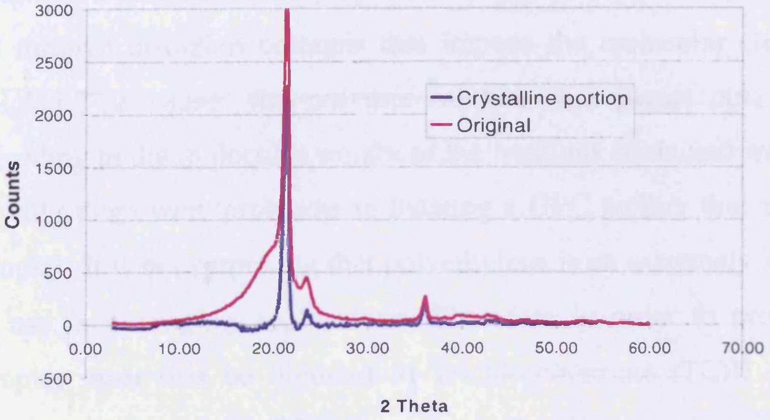


Figure 5.11 Crystalline trace and semi-crystalline trace with Compton scattering removed.

The crystalline curve and the original semi-crystalline curve were then normalised by multiplication with the square of their intensities (from Equation 5.3) and plotted on the same graph for comparison. At this point the range of useful data was determined by looking for negative or spurious points in the set.

The two curves were numerically integrated using a trapezium-rule approximation to determine the area under each curve. The ratio of these two integrals (i.e. the weight of the calculated crystalline peaks divided by the sum of the weights of the amorphous background and the crystalline peaks) was the degree of crystallinity. This data was then transferred to a separate but dynamically-linked spreadsheet because file size was becoming a problem, causing computer processing instability.

This data was then plotted as a function of the particular property that was under consideration, for example, the results were used to display the change in percentage crystallinity with the number of processing cycles that the material had undergone.

No estimation was available for the accuracy of this method. It was evident from the calculation steps that some results were more accurate than others, depending on the user's ability to read the Compton scattering value. The overall accuracy of XRD in conjunction with this method is discussed later.

## 5.7 Measurement of molecular weight distribution via Gel-Permeation Chromatography (GPC)

The theory of the operation behind GPC analysis is covered in Chapter 2. Basically GPC is a method of size-exclusion chromatography that classifies the molecular weight of a polymer mixture by dissolving it in a solvent to form a gel and passing the gel through diffusion columns that impede the molecular chains according to their weight. This causes the polymer mixture to separate out and thus be classified according to the molecular weight of the fractions contained within it.

Initially there were problems in locating a GPC facility that would test polyethylene samples. It is not surprising that polyethylene is an extremely stable compound, hence its use in packaging applications. Therefore in order to process PE via GPC any samples must first be digested in Trichlorobenzene (TCB) at 160°C. Most of the commercially available GPC apparatus in the UK are not configured to run using such chemicals and at such high temperatures. GPC is normally used at room temperature to characterise less stable polymers, such as pharmaceuticals and other polymeric mixtures of lower molecular weight.

The only compatible facility was located at Rapra Technology Limited, Shropshire, UK. Rapra Technology is an independent plastics and rubber consultancy, providing technology and information services for the polymer industry. Due to the high experimentation costs, only 20 samples were processed, thus the most pertinent samples were chosen.

Data already gathered based on the information from the mechanical properties in conjunction with the XRD results provided clues of which samples would be most useful to test. The information that therefore required further analysis by GPC at this stage was decided as:

- Material cycling tests.
- Addition of packaging tape.
- Alloying tests.

The hardware used was a polymer laboratories GPC220 instrument fitted with a Viscotek differential pressure (viscosity) detector. The equipment is computer-controlled and is normally configured to run a series of tests in succession, which is useful for comparison testing as was the case for this work. This allows the loading of a reference polymer, to which the others can be compared to.

The polymer was first made into a gel by being dissolved in Trichlorbenzene at 190°C to a concentration of about 0.1% by weight and immediately inserted into sample injection vials on a rotating carousel, shown in Figure 5.12. The samples were then injected into the GPC columns, where they were processed at 160°C. Passing the gels directly from dissolution to processing was done to minimise degradation to the polymer sample as the TCB causes the polymer chains to disintegrate after prolonged exposure.

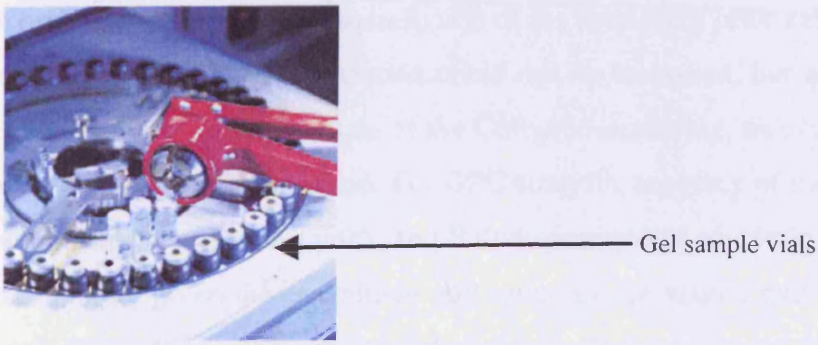


Figure 5.12 Sample injection carousel

The gel-phase sample was then allowed to pass through the filter columns at the rate of 1 ml per minute. The columns were two 300 x 7.5mm tubes containing 10μm Plgel filter beads, shown in Figure 5.13.

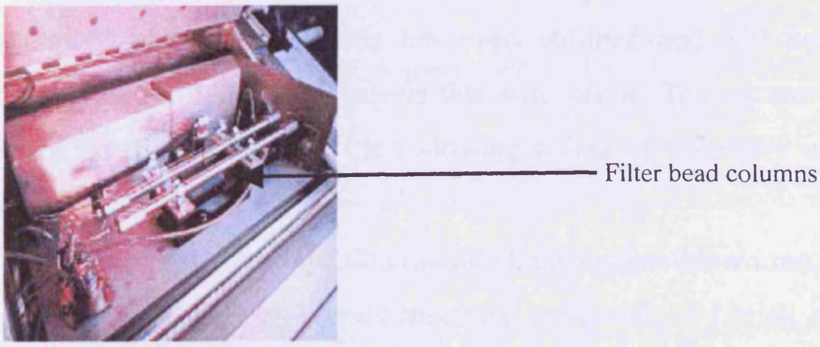


Figure 5.13 The GPC columns

After passing through the columns, concentrations of the gel were measured at the detector and logged into a computer. This was then used to build up a chromatograph of the polymer sample. The results (values of Mn, Mw and PI, along with the data plots of intensity versus mwt) were returned in electronic format and loaded into a spreadsheet package for further analysis.

## 5.8 Accuracy and errors associated with the experiments

For the tensile testing, measurement was made with a load cell to the nearest 0.01kN, with a tolerance of ± 10%, due to the test speed of 500mm/min, as shown in EN ISO 527-1. Elongation was to the nearest 1mm, although accuracy of reading was probably closer to 2mm. MFI measurement, in accordance with the standard from which it was produced was within 5% of reading, which was 0.006 g/10 min for the least viscous and 0.075 g/10 min for the most viscous polymer.

Calculation of crystallinity content was more difficult to quantify, due to the interpretation required when reading background scattering values and data sets. Compton scattering was generally 2% of the maximum peak value for all the data sets calculated. Human interpretation could not be measured, but assuming that this was no greater than the magnitude of the Compton scattering, an overall accuracy of ± 4% would be a logical estimation. For GPC analysis, accuracy of molecular weight was to within 100 atomic mass units, and Polydispersity was to within 0.1. This was deemed acceptable, given the magnitude and range of the results returned by the apparatus, typically $2\times10^4$ mass units and Polydispersity Index of around 10.

## 5.9 Summary

Mechanical testing and chemical analysis has been performed on the samples, in line with the test specifications. This has enabled comparisons to be made between life-cycle factors and the changes in physical properties of the polymers tested. The accuracy of the experiments has been outlined and will be shown to be within acceptable limits for the analysis that will follow. Testing was performed within the specified limits, although the following points of necessary compromise should be borne in mind:

- Samples were injection moulded, rather than blown into film for simplicity as it is difficult and time-consuming to blow-mould small amounts of material.
- Melt-phase mixing was not as intense as would be encountered if using an extrusion machine, where material can be continuously blended until high levels of homogeneity are achieved. This was due to the small amounts of polymer used per sample in testing and the unavailability of such equipment.
- GPC analysis was not performed on all the samples due to financial constraints.

Chapter 6 shows the results and interpretation of the data collected using the methodologies shown.

# Chapter 6 – Results and discussion

## 6.1 Introduction

This chapter highlights the results and discussion relating to the experimental outline shown in Chapter 5. The results are presented by subdivision into the life-cycle factor under investigation and the experimental testing that was performed on the material in question. A summary of the effect of each life-cycle factor is given after the material testing results have been presented.

Since the results are concerned with how a material property changes with exposure to different life-cycle factors, the original properties are shown in Table 6.1. This table shows the nominal material property values for the polymers used in the study. These values are "ground states" i.e. no life-cycle factor (heat cycling, contamination, etc) has been applied. Where changes to material properties are expressed in terms of a percentage of the original value, the original value is listed in Table 6.1. The full and original set of test data for each test, including sample dimensions and curves can be found in Appendix H.

Table 6.1 Material property data for the five polymers used in the experiments.

| Material | UTS MPa | Maximum elongation % | MFI g/10 min | Crystallinity % | Mn | PI |
|---|---|---|---|---|---|---|
| Virgin LDPE | 19.1 | 96.8 | 1.50 | 24.2 | 22250 | 7.9 |
| Erema mixture | 17.9 | 77.3 | 1.05 | 34.9 | 22950 | 4.2 |
| HDPE bags | 38.0 | 24.7 | 0.08 | 70.1 | 12450 | 13.5 |
| LDPE packaging film | 31.6 | 36.7 | 0.52 | 44.6 | - | - |
| Broad specification virgin LDPE* | 29.5 | 44.3 | 0.45 | 32.2 | - | - |

*Broad specification LDPE is virgin LDPE with a wide specification (i.e. a large PI) due to the mixture of polyethylenes contained within it. For packaging applications the material is widely used because narrow specifications are not always critical.

## 6.2 Material cycling tests

### 6.2.1 Tensile testing

Figure 6.1 shows the relationship between UTS and the number of processing cycles for four types of polyethylene, namely virgin LDPE, the Erema product, carrier bag HDPE and the supermarket LDPE film. The results are expressed in terms of the percentage change from the original UTS values at zero heat cycles, the values of which are shown in Table 6.1. A best- fit spline curve was applied to each data series. The error bars shown on each point indicate the range of the averaged test data that was used to make each point. There is an increase in UTS for each material as the number of processing cycles is increased.

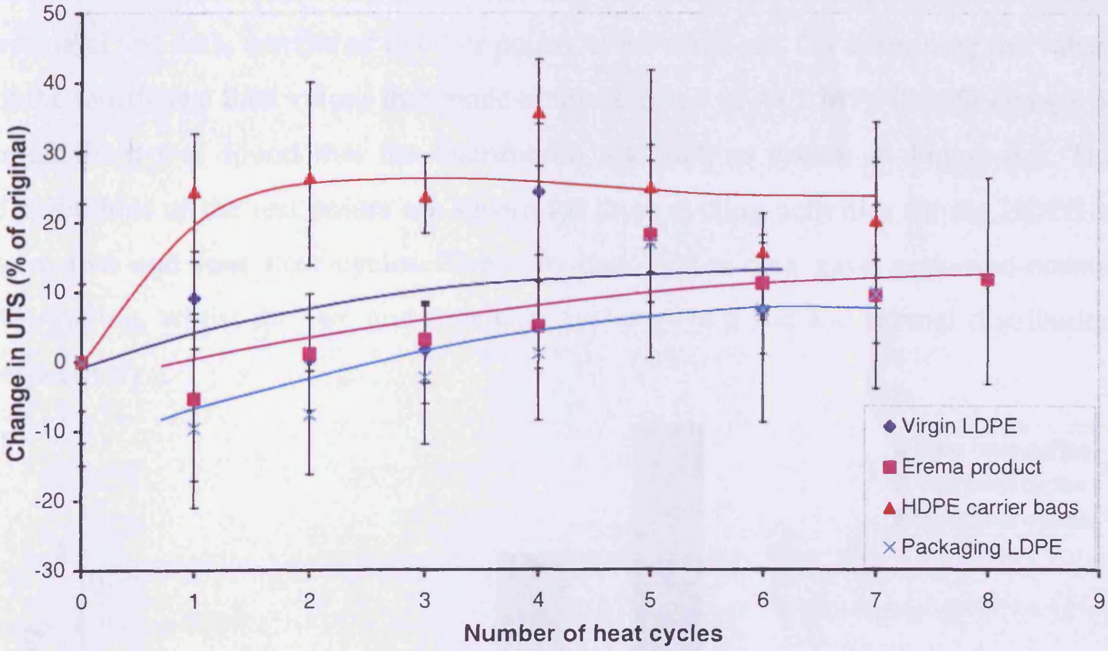


Figure 6.1 The percentage change in UTS of four different polymers with number of heat processing cycles.

As the data in Figure 6.1 shows, the tensile strength has changed in such a way that all of the materials tested exhibit a strengthening effect, which is seen as brittleness when coupled with a decrease in maximum elongation. This would be considered detrimental in packaging applications where ductility is important.

Virgin LDPE shows an increase in UTS of around 10% over six processing cycles. The Erema processed PE also shows a increase in UTS of around 10% over the same range, indicating that this material behaves similarly in recycling compared to virgin LDPE. The supermarket packing film also shows an increase in UTS of around 10%

over six processing cycles, however the response curve increases less rapidly than the other LDPE based materials discussed. The carrier bag HDPE material shows an increase in UTS of around 20% over six processing cycles, although it showed a significant 30% increase during the initial three heat cycles, followed by a decrease. This material produced the most amount of scatter, attributed to interference from poorly mixed printing dyes used in the labelling of the bags. The expected increases in UTS can be attributed to the chain breaking / realignment undergone during the processing / heat cycles, as shown in Section 6.2.5. The increase in brittleness was also linked to these effects.

Some of the data points in the Figure 6.1 show a larger range than expected. The UTS point at two heat cycles for the carrier bag HDPE shows a large variation for the averaged test data, compared to other points in the same set. On examining the values of the tensile test data values that made up the average of 48.1 MPa (26.5% change of original), it was found that the distribution was flat, as shown in Figure 6.2. The distributions of the test points are shown for three cycling activities for the HDPE at zero, two and four heat cycles. The zero heat cycles data gave a skewed-normal distribution, whilst the two and four heat cycles gave a flat and normal distribution respectively.

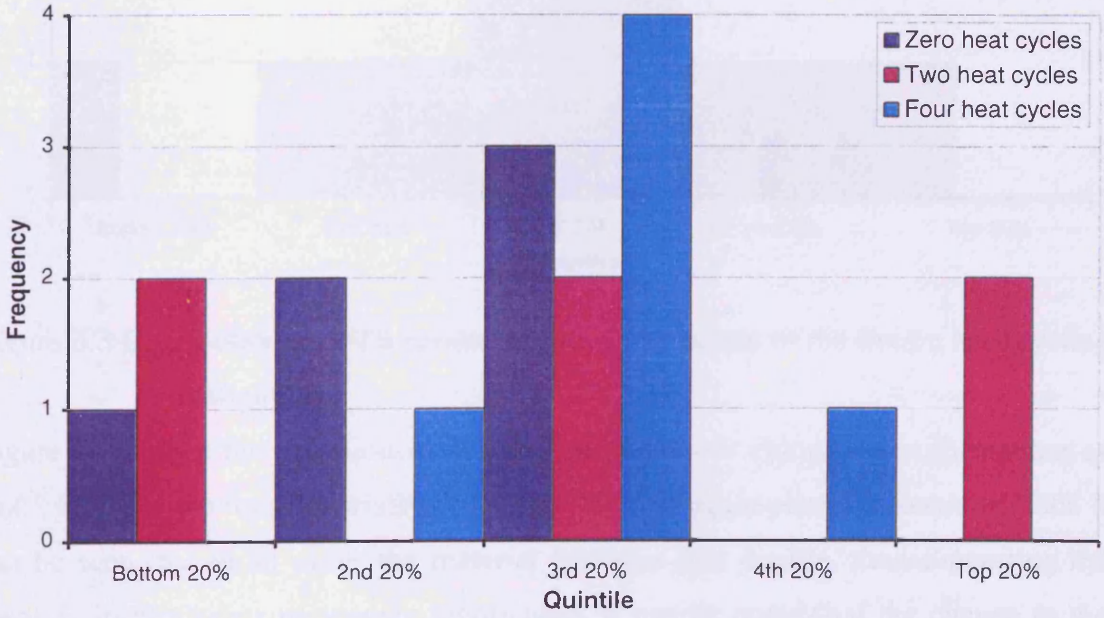


Figure 6.2 Distribution of UTS results of carrier bag HDPE for three heat cycling investigations.

There was no value to which the two heat cycles test data centred on, implying that more test data would have been useful in determining a reliable value for the average UTS. As per the test standard [83] only six material samples were tested per data point. It was assumed that this was sufficient to produce reliable average values. This indicated that the material was non-homogeneous and six samples were insufficient to give a normal distribution. However, UTS was not one of the critical parameters and therefore any scatter did not have a major influence on the life-cycle testing.

The UTS values at one and eight heat cycles for the Erema material also had a fairly flat distribution, as shown in Figure 6.3, again indicating some material non-homogeneity. The figure shows that at five and six heat cycles the data follows a normal distribution.

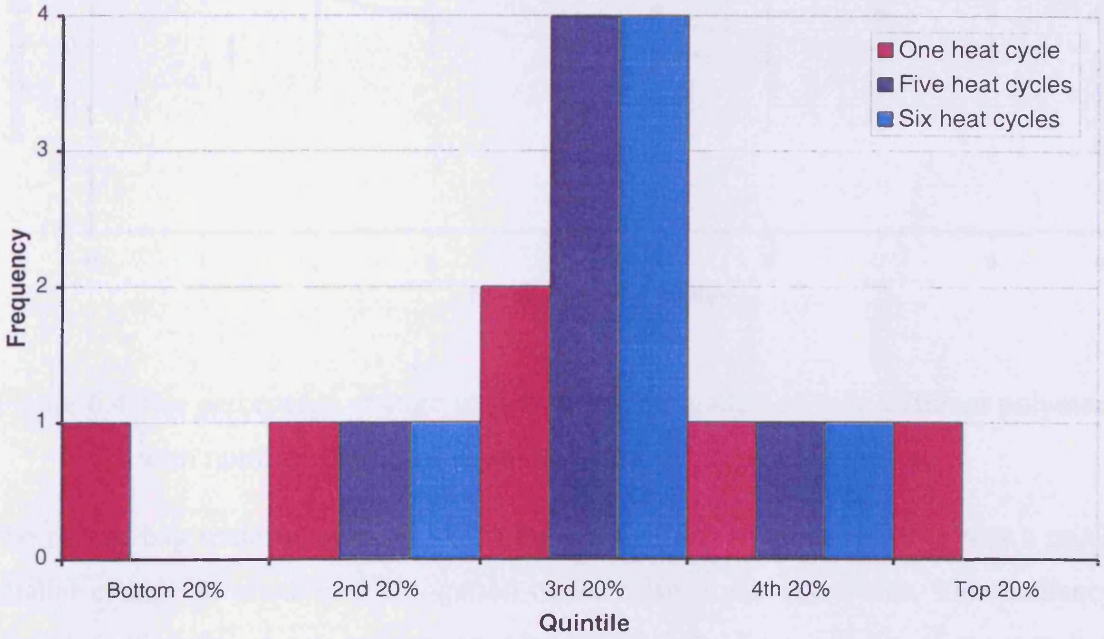


Figure 6.3 Distribution of UTS results for three test points in the Erema heat cycling investigation.

Figure 6.4 shows the variation in percentage maximum elongation with number of heat cycles for the four materials with a best fit curve again placed through the data. It can be seen that in all cases the material becomes less ductile, thus supporting the increase in brittleness previously highlighted. It can be noted that the change in the carrier bag HDPE was the smallest in magnitude, which was attributed to its morphology as explained in Section 6.2.5. The Erema PE showed the largest amount of scatter, which was attributed to its lower homogeneity as it came from a mixed feedstock.

The maximum elongation of virgin LDPE reduced by 35% over six processing cycles from its original value, compared with the Erema material which was reduced by 15% over the same range. The supermarket packing film showed a decrease in maximum elongation of 45% over six processing cycles, which was the largest reduction in the maximum elongation for all the materials.

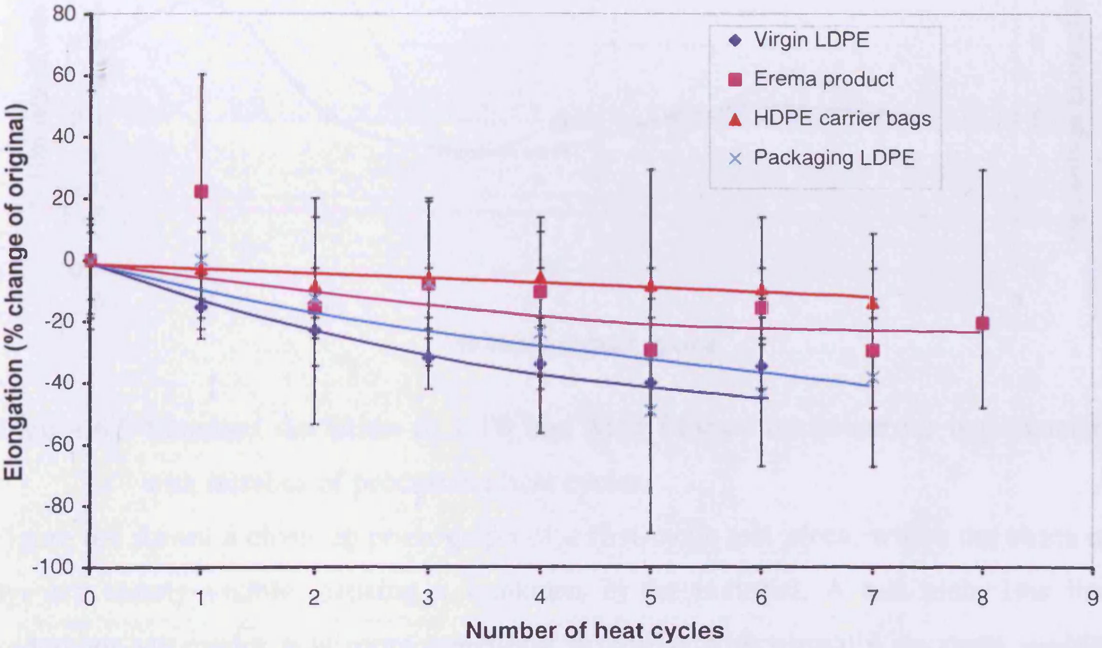


Figure 6.4 The percentage change in maximum elongation of four different polymers with number of heat processing cycles.

The carrier bag material was an exception to the other materials. There was a much smaller change in maximum elongation of only 10% over six cycles. This tendency for reduced brittleness can be explained by studying the homogeneity of the material. The standard deviation of cycling tests from process step zero to step seven becomes consistently smaller, as shown in Figure 6.5 and explained by an improvement of the mixedness of the material as it undergoes successive injection cycles. There are also molecular factors involved, which are discussed later.

This reduction in standard deviation with increasing number of heat cycles was attributed to the effect of the dyes used in printing the logos on the bags themselves. Initially the dyes do not mix well with the polyethylene, producing a heterogeneous mixture, which introduces weakened strata through the material.

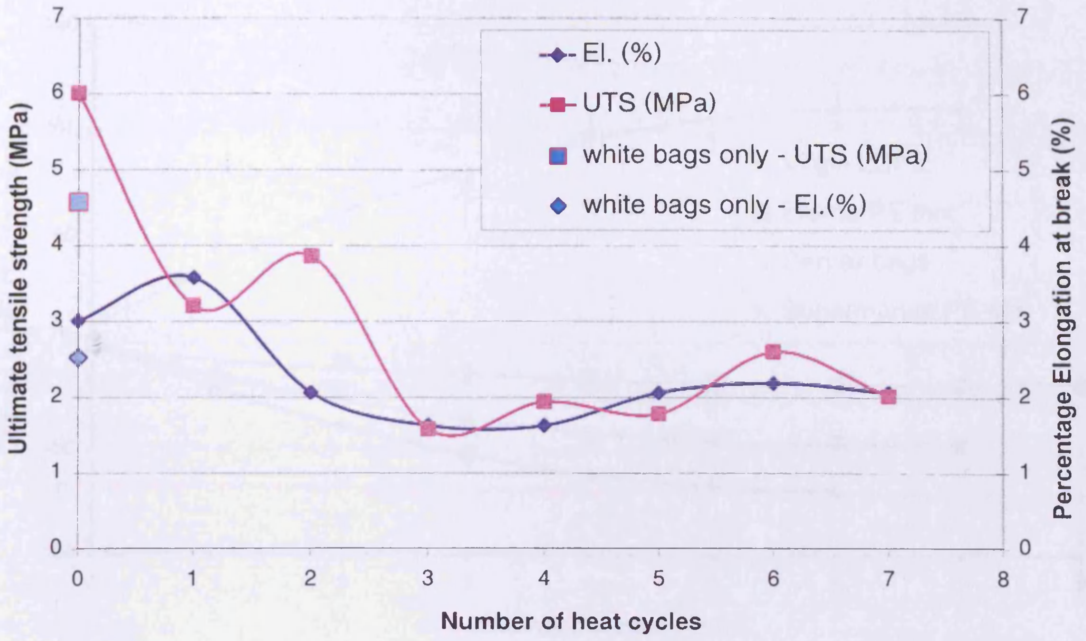


Figure 6.5 Standard deviation of UTS and Max Elongation of carrier bag material with number of processing heat cycles.

Figure 6.6 shows a close-up photograph of a first-cycle test piece, where the strata of dye are clearly visible, causing a weakness in the material. A test piece that had undergone six cycles was more consistent in colour with virtually no strata visible, implying that the sample was more homogeneous (a more even dye distribution) due to the successive mixing of the re-moulding and pelletisation process.

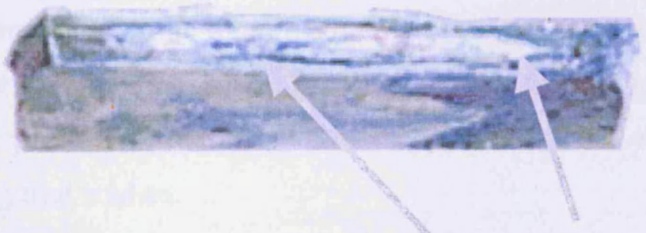


Figure 6.6 Close up photograph of poorly-mixed recycled carrier bag material that has undergone one processing heat cycle.

### 6.2.2 MFI measurement

Figure 6.7 shows the change in MFI as the materials were heat cycled. All the polymers tested show a reduction in MFI, except the HDPE carrier bag material, which showed a substantial increase.

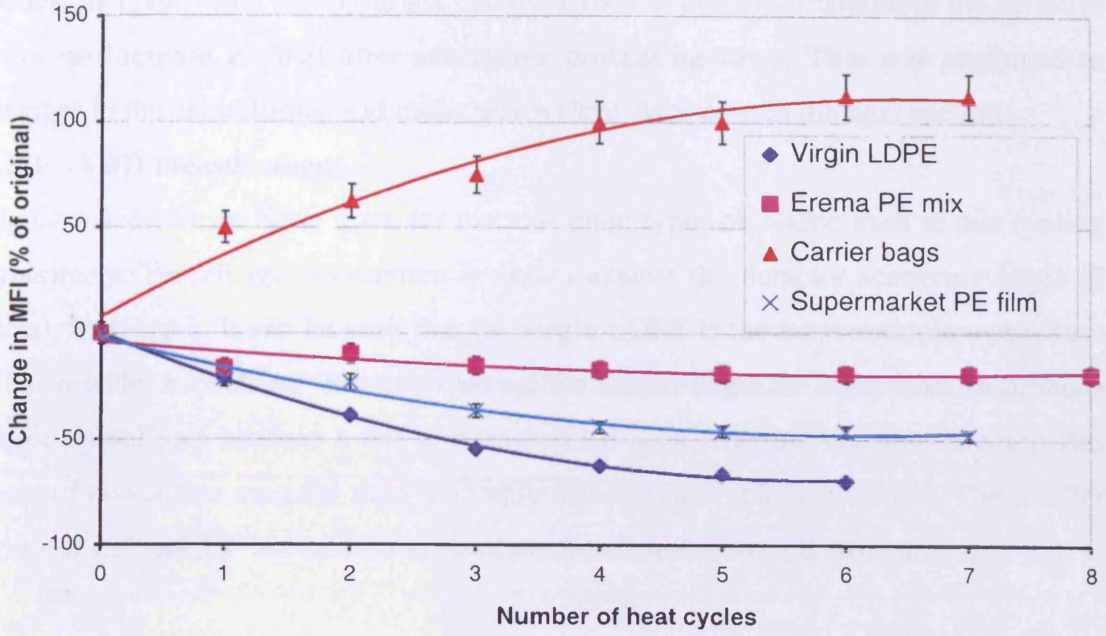


Figure 6.7 The percentage change in MFI of four different polymers with number of heat processing cycles.

The MFI of the virgin LDPE material, which was 1.5 g/10 min at zero heat cycles, reduced by 70% over six cycles. Although the change in UTS was not significantly large, the 35% reduction in maximum elongation and the 70% reduction in MFI (based on original values at zero heat cycles) would be sufficiently large to raise concerns over the application and manufacture of heavily reprocessed LDPE films.

The MFI of the Erema material, which was 1.05 g/10 min at zero cycles, reduced by 19% over six cycles. Although a comparatively small reduction, such a MFI could cause problems in the manufacture of small-gauge films [3], but in general industrial practice this material would be alloyed with a polyethylene product of much higher MFI to produce a mixture within acceptable criteria, which is presented later in the alloying trial studies.

The MFI of the supermarket packing film, which was 0.5 g/10 min at zero cycles, reduced by 46% over six cycles. This reduction in MFI would probably cause problems in the manufacture of small-gauge films because the material would be more viscous and not extrude so readily, limiting the application of this material after a series of processing cycles. It is worth mentioning that the MFI of this material was still higher than that of the carrier bag material, although its UTS was lower, prompting the possibility of a potential market manufacturing this material into carrier bag-type applications. The carrier bag material, which was 0.08 g/10 min at zero cycles, increased by 113% over six cycles. This was the only material in the series to show an increase in MFI after successive processing steps. This was attributed to changes in the crystallinity and molecular weight, as shown in the next section.

### 6.2.3 XRD measurement

Figure 6.8 shows an XRD trace for the four main types of plastic used in this cycling experiment. Percentage occurrence is drawn against the detector scattering angle (2 theta), in degrees. It can be seen that the virgin LDPE is the most amorphous because it has a wider broadband 'hump', whereas the carrier bag film is the least amorphous (most crystalline) because it has a more defined peak structure and thus it comprises more of crystalline material than randomly arranged amorphous material. The smaller peaks at 23° and 36° are smaller crystalline details in the overall structure.

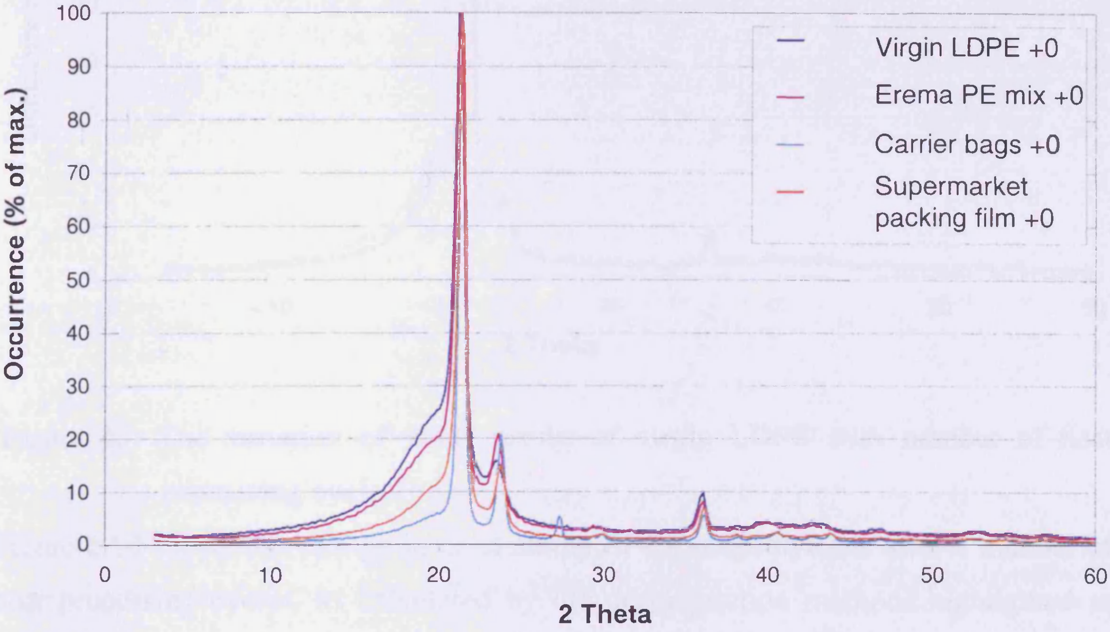


Figure 6.8 XRD results for four different types of polyethylene material, all of which have undergone no additional heat processing cycles.

What is also evident from these results was that the difference between these four materials is relatively subtle, given that two of these materials are at opposite ends of the packaging polyethylene spectrum in terms of their physical properties. It is therefore not logical to present the XRD results in this fashion, but rather as a measure of crystallinity versus the material type. This was evident in the initial XRD results for the cycling tests, where cycle-to-cycle changes were difficult to detect from the data sets.

Figure 6.9 shows the XRD results of the virgin LDPE cycling test and it is evident from this figure that the trace was hard to interpret because the difference between the seven traces was very small. For this reason, XRD results are presented as shown in Figure 6.10. The changes in crystallinity versus cycle number are far easier to determine and interpret.

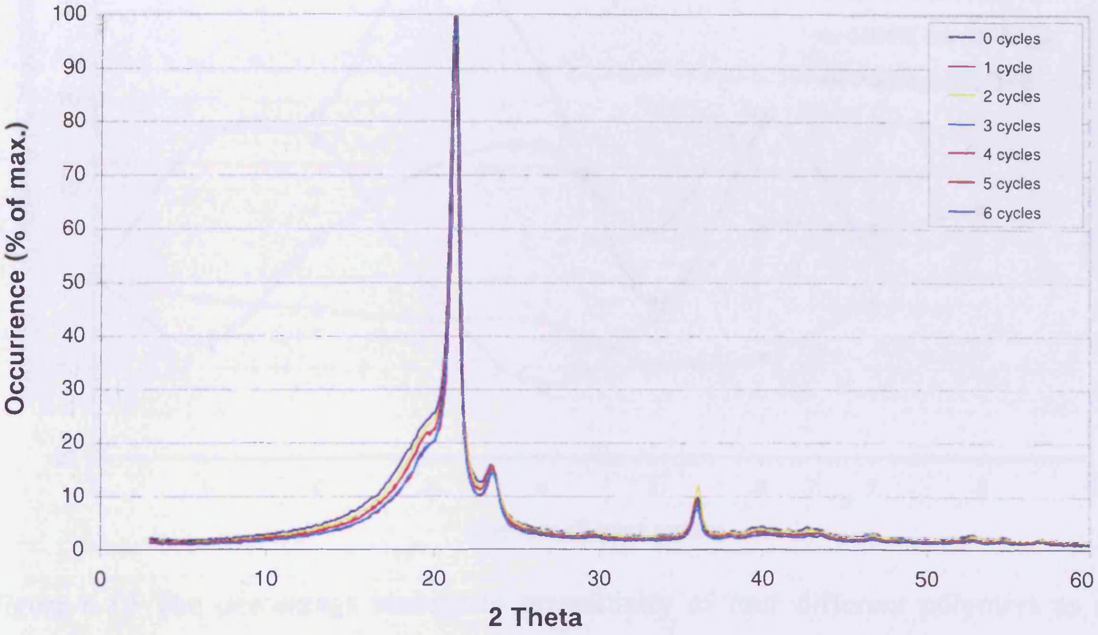


Figure 6.9 The variation of XRD results of virgin LDPE with number of heat processing cycles.

Figure 6.10 shows the change in crystallinity of the polyethylenes after a number of heat processing cycles, as calculated by the deconvolution methods highlighted in Chapter 5. The original (zero heat cycle) crystallinity values can be found in Table 6.1, which also illustrate that the more amorphous materials, such as virgin LDPE, are more ductile than the crystalline materials, such as carrier bag HDPE.

The Virgin LDPE shows a 15% increase in crystallinity over six cycles, although there is scatter evident in the data. At five cycles there appears to be a sudden reduction, but this was more likely due to a spurious data point, possibly from poor mixing of the prepared sample or reduced diffraction at higher theta values. The Erema mixture also shows scatter and an increase in crystallinity of 6% over six processing cycles.

The carrier bag HDPE is the only material to show a consistent decrease in crystallinity over the processing cycles. Its crystallinity reduced by 5% over six cycles. This change was contrary to the other polyethylene materials tested. There was also a correlation with the change in MFI as shown in Figure 6.7. The packaging LDPE film behaves in a similar fashion to the virgin LDPE inasmuch as it increases in crystallinity by 15% over six cycles although the virgin LDPE shows more scatter.

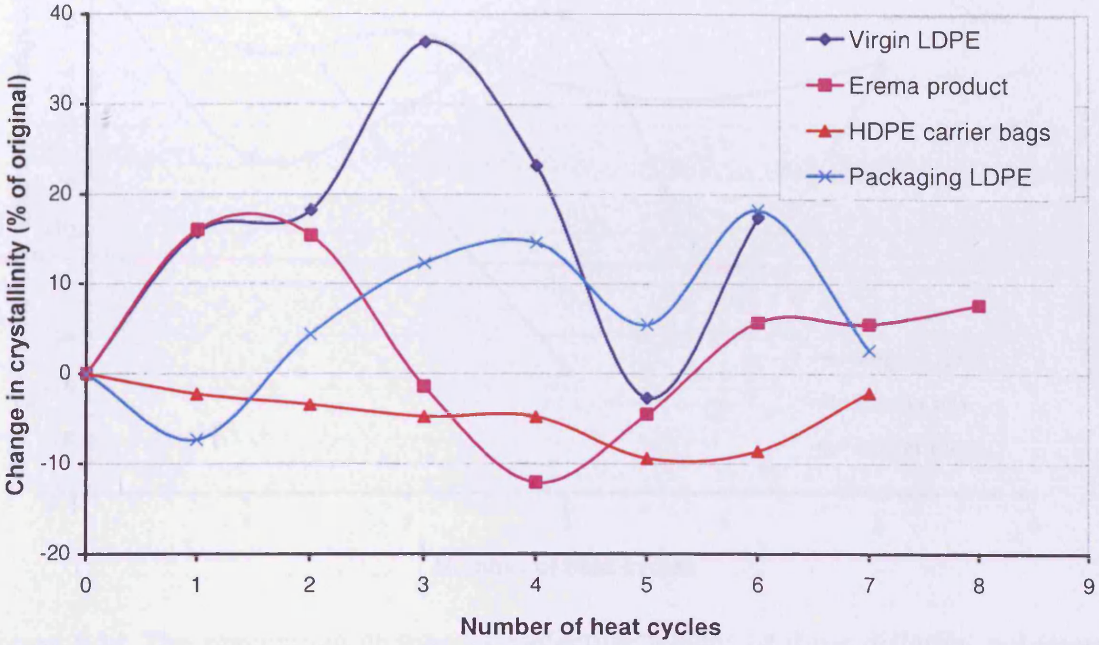


Figure 6.10 The percentage change in crystallinity of four different polymers as a function of number of heat processing cycles.

### 6.2.4 GPC results.

Figure 6.11 shows the change in molecular weight as a function of heat processing cycles. The results for the Erema mixture are less consistent compared to that of the virgin LDPE or packaging HDPE. This was probably due to inconsistent mixing in the processing stage.

All three results point to the same general trend, that the recycling process causes the average molecular weight of the polymer to decrease, implying that the polymer chains are being broken as a result of the heat processing. For the Erema and virgin LDPE material, the decrease was approximately 5% over five processing cycles, although there was a large amount of scatter evident in the Erema sample. The HDPE material decreased by 16% over three cycles, implying that the chain-breaking process was more pronounced in linear polymers such as HDPE. The more highly-branched nature of the non-linear LDPE molecules gives them greater cohesion during the heating processes. It was understood that there is a certain (although unknown) amount of HDPE in the Erema sample, which would account for its tendency to reduce in molecular weight more readily than the virgin LDPE. This could also account for the large amount of scatter in the data, since HDPE/LDPE ratio and distribution was not known.

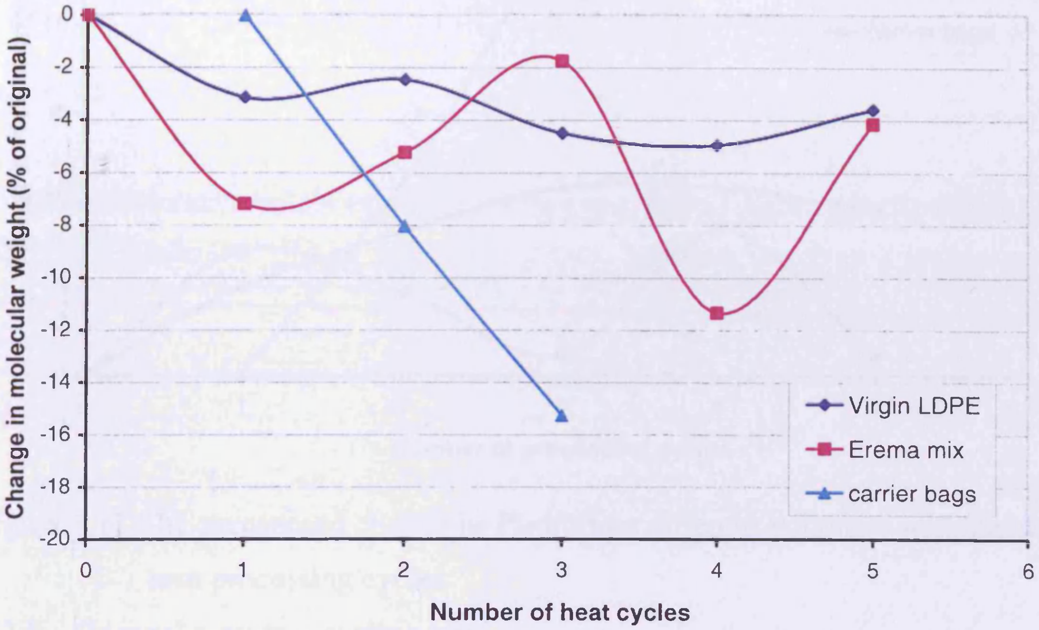


Figure 6.11 The percentage change in molecular weight of three different polymers with number of heat processing cycles.

Figure 6.12 shows the effect that processing has on the PI. Polydispersity data appeared to be more consistent than the molecular weight data. The data shows that the virgin LDPE increased by 10% over five heat cycles from its original value. The Erema mixture again showed large scatter, but had the potential to increase its PI by up to 8% over the range shown. The packaging HDPE sample increased its PI more readily, at 26% over three cycles. The HDPE is therefore changing in molecular mass more readily than the other materials studied.

This confirms that the processing causes individual polymer chains to break into smaller ones, rather than combining to make larger ones. It also demonstrates that not all of the polymer chains are undergoing this breaking process. It appears that only a certain amount of chains are being broken per heat cycle, which seems to increase as the processing cycles increase. Larger molecules are more likely to retain their mass, probably due to branching and inter-linking.

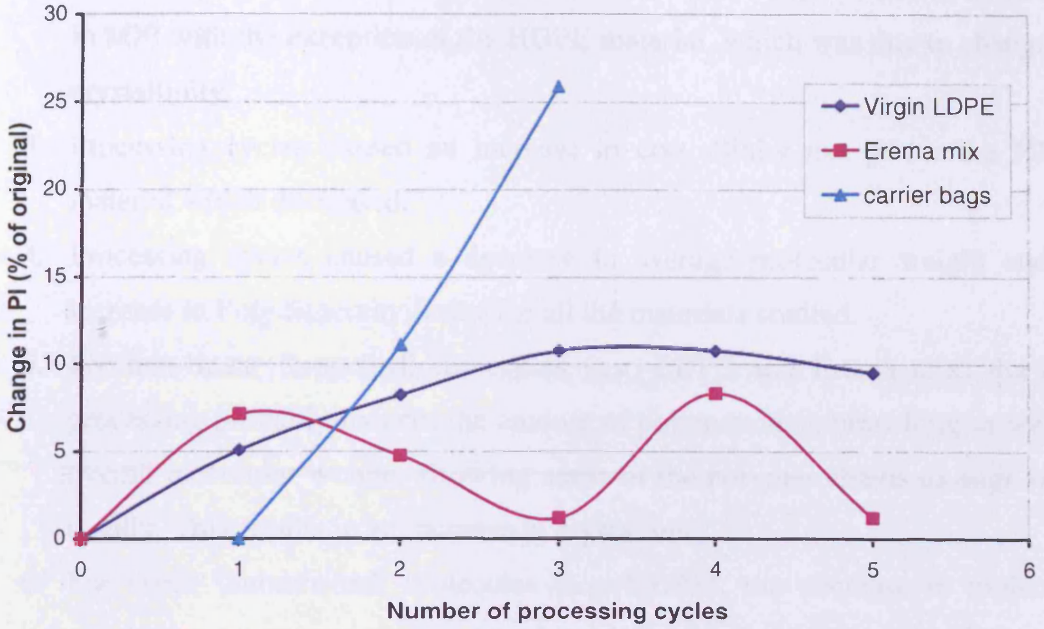


Figure 6.12 The percentage change in PI of three different polymers with number of heat processing cycles.

### 6.2.5 General results – cycling tests

Table 6.2 shows a review of all the property changes shown in the material cycling tests.

Table 6.2 Overall results of material cycling tests.

| Material | UTS | % Elong. | MFI | Crystallinity | MWT |
|---|---|---|---|---|---|
| Virgin LDPE | Increased | Decreased | Decreased | Increased | Decreased |
| Erema PE mixture | Increased | Decreased | Decreased | Increased | Decreased |
| Carrier bag HDPE | Increased | Decreased | Increased | Decreased | Decreased |
| Recovered supermarket PE film | Increased | Decreased | Decreased | Increased | - |

The following observations can be made about the heat-cycling of polyethylene materials:

1. Processing cycles made all of the materials tested more brittle.

2. Processing cycles made all of the materials harder to process due to a decrease in MFI with the exception of the HDPE material, which was due to changes in crystallinity.
3. Processing cycles caused an increase in crystallinity except for the HDPE material which decreased.
4. Processing cycles caused a decrease in average molecular weight and an increase in Polydispersity Index for all the materials studied.
5. For non-linear (branched) molecules (e.g. LDPE and Erema mix) the heat processing probably reduces the amount of polymer chain branching as well as overall molecular weight, allowing some of the polymer chains to align more readily. This results in an increase in crystallinity.
6. For linear (unbranched) molecules (e.g. HDPE), the decrease in molecular weight due to process cycling causes an increase of polydispersity, because it lowers the effectiveness of the polymers to align therefore decreasing the crystallinity.
7. The effectiveness of the mixing prior to extrusion has an effect on the material properties, with materials that have non-homogeneous concentrations of dye being more brittle than well-mixed samples.

## 6.3 Addition of LLDPE film

### 6.3.1 Tensile testing

Figure 6.13 shows the relationship between the change in UTS and the amount of LLDPE film added to two different types of polyethylene by mass. A best fit curve has been applied to both sets of data. There was a small change in UTS for each material as the LLDPE content was increased.

The figure shows that when mixing the LLDPE with the two types of PE, the change from 0% to 20% LLDPE was different for the materials, i.e. the virgin LDPE decreased in UTS, whilst the Erema mixture increased. It should be made clear, however that the UTS of the LLDPE itself was only 2.0 MPa greater than the Virgin LDPE and 4.7 MPa greater than the Erema mixture. Thus, although it appears that the UTS change is dependent on the percentage of LLDPE added, the overall changes are only subtle and the range of the study was too small to be conclusive. Therefore it is more logical to study the mixing of materials with bigger differences in their tensile properties in order to see how alloying them together changes their UTS.

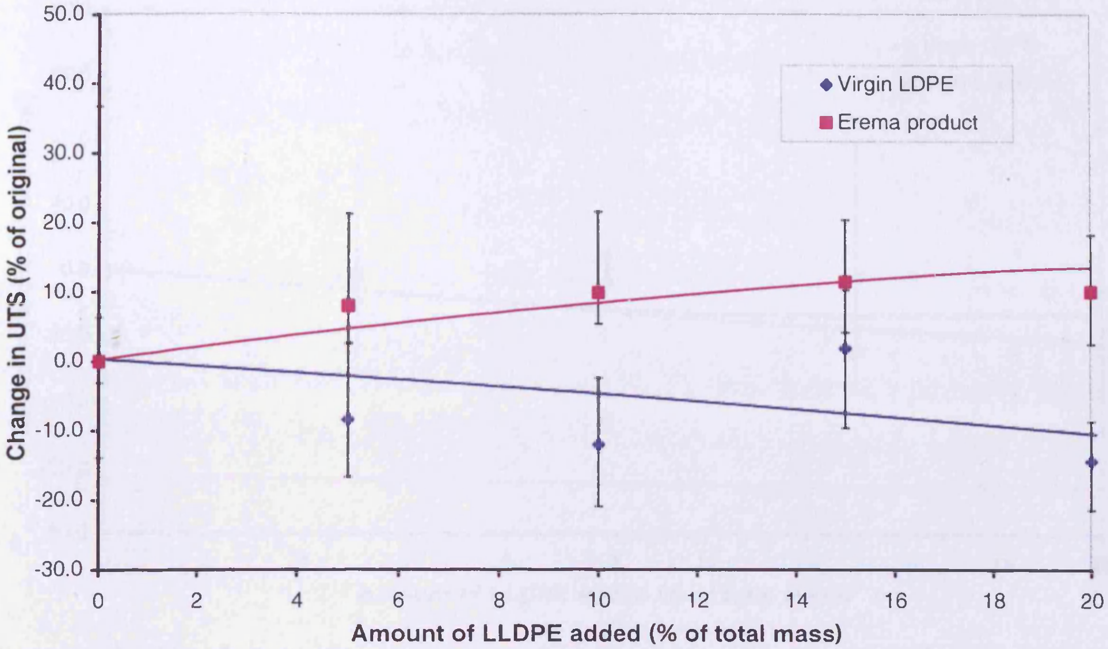


Figure 6.13 The percentage change in UTS of two different polymers with LLDPE addition

Figure 6.14 shows the same material tests with the change in maximum elongation for the two materials with increasing amounts of LLDPE. There was some scatter in the data, making the overall trends difficult to interpret, which can be attributed to inconsistent mixing prior to injection moulding during the preparation stage.

The magnitude of the changes over the range examined were similar, although the Erema mixture showed more scatter in individual test points as well as in its overall trend. Over the 20% range of LLDPE added to the polymers, a decrease in maximum elongation of 15% and 20% was seen for the virgin and Erema mixture respectively. The maximum elongation of the LLDPE itself was some 40% less than the materials examined.

The figure shows that as an injection moulded plastic, LLDPE is less ductile than the two materials studied, but quantifying its effect as a contaminant was limited by the accuracy of the results. As with the UTS results, additional data is required to assess the effect of mixing polymer compounds together, preferably using polymers with greater differences in their tensile properties. This is presented in the alloying section of these results.

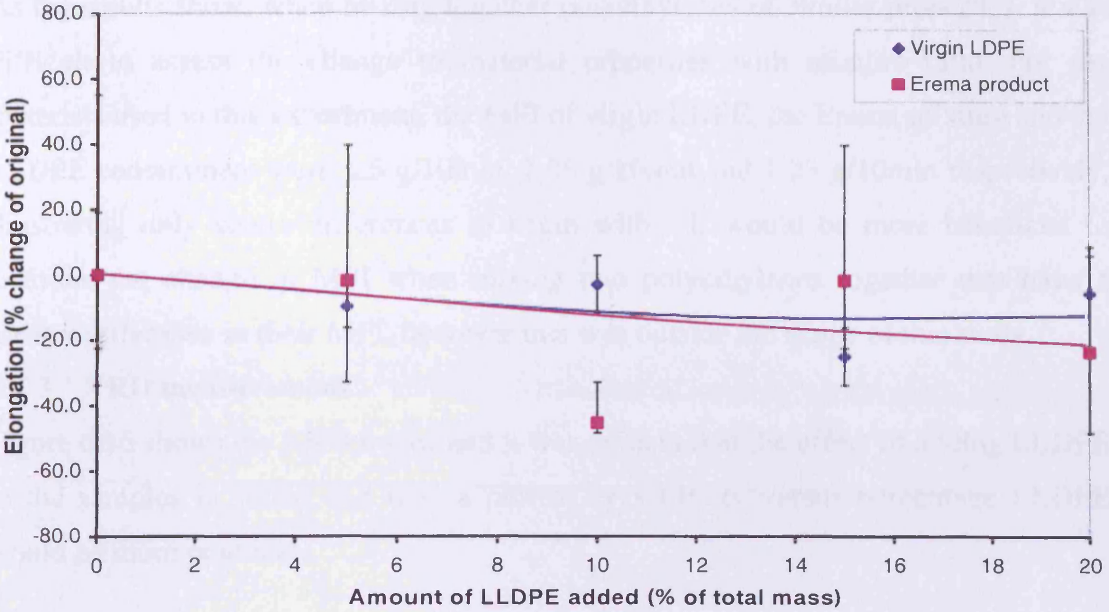


Figure 6.14 The percentage change in maximum elongation of two different polymers with LLDPE addition

### 6.3.2 MFI measurement

Figure 6.15 shows the change in MFI as increasing amounts of LLDPE are added. It was evident in the results that the change in MFI for the Virgin LDPE with increasing amounts of LLDPE was a consistent decrease, however the Erema mixture with LLDPE remained constant over the 0% to 20% range examined.

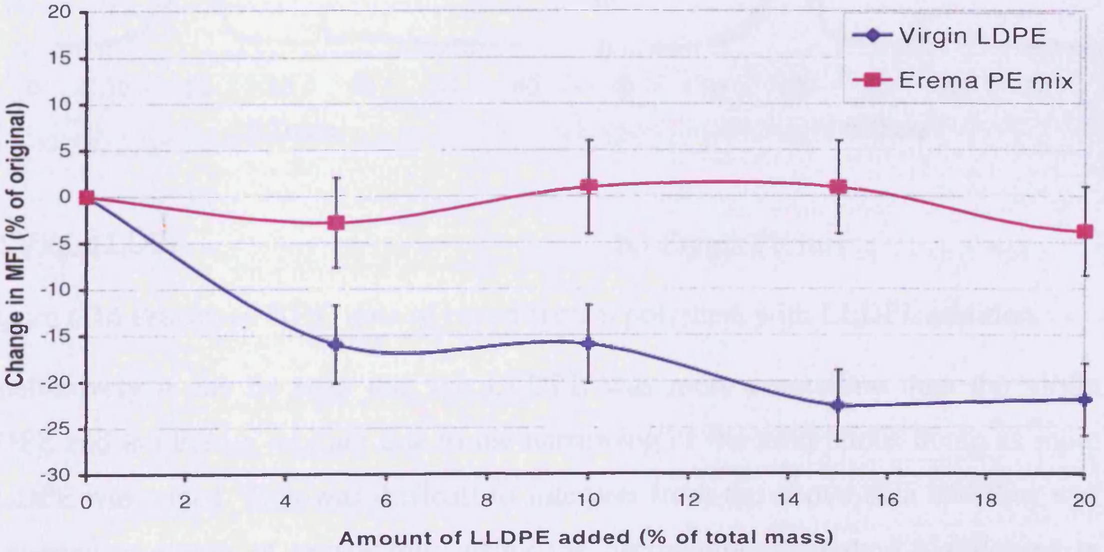
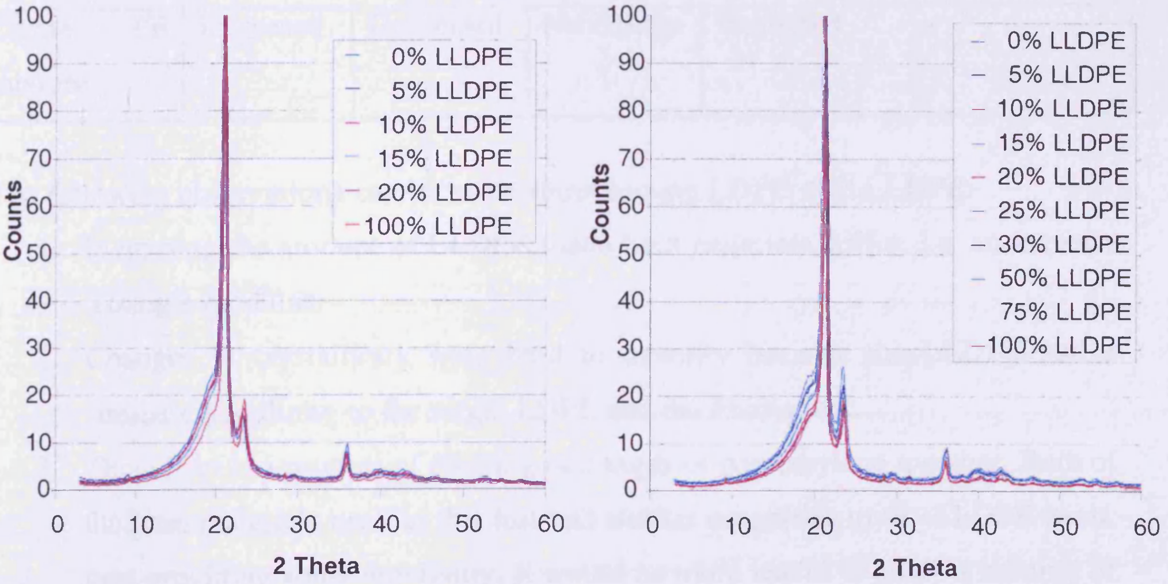


Figure 6.15 The percentage change in MFI of two different polymers with LLDPE addition

As the results show, when mixing together polyethylenes of similar properties, it was difficult to assess the change in material properties with mixture ratio. For the materials used in this experiment, the MFI of virgin LDPE, the Erema mixture and the LLDPE contaminant were 1.5 g/10min, 1.05 g/10min and 1.25 g/10min respectively, illustrating only subtle differences to begin with. It would be more beneficial to examine the change in MFI when mixing two polyethylenes together that have a greater difference in their MFI, however this was outside the scope of this study.

### 6.3.3 XRD measurement

Figure 6.16 shows the XRD traces and it was evident that the effect of adding LLDPE to the samples is subtle and thus a plot of crystallinity versus percentage LLDPE would be more practical.



a.) Virgin LDPE

b.) Erema PE mix

Figure 6.16 Processed XRD data of two different polymers with LLDPE addition.

Qualitatively it can be seen that the LLDPE was more crystalline than the virgin LDPE and the Erema mixture due to the narrowing of the amorphous hump as more LLDPE was added. This was difficult to interpret from the above data and thus was converted to values of crystallinity using the deconvolution method highlighted in Section 5.6.

Converting the XRD results to crystallinity showed that there was a large amount of experimental scatter in the relationship between the LLDPE content and the crystallinity. No specific trend was visible in this data to suggest that the mixing of the polyethylenes and LLDPE produced a consistent change. This was likely due to the accuracy of the crystallinity calculations coupled with the large amounts of scatter in the XRD data (± 40%). This again suggests that alloying of polyethylenes be examined on a greater scale, rather than studying the subtleties of adding LLDPE to LDPE.

### 6.3.4 General results – addition of LLDPE

The effect of adding LLDPE to PE is shown in Table 6.3.

Table 6.3 Addition of LLDPE to PE

| Material | UTS | % Elong. | MFI | Crystallinity | MWT dist. |
|---|---|---|---|---|---|
| Virgin LDPE | Decreased | Decreased | Decreased | Increased | - |
| Erema PE mixture | Increased | Decreased | No change | Increased | - |

The following observations can be made about mixing LDPE with LLDPE:

1. Increasing the amount of LLDPE made both materials stiffer, i.e. an increase Young's modulus.
2. Changes in crystallinity were hard to quantify because the LLDPE had a similar crystallinity to the virgin LDPE and the Erema mix.
3. This effect is a process of alloying two kinds of polyethylene together. Both of the base materials used in this test had similar properties to the LLDPE itself, thus providing some ambiguity. It would be more useful to study a mixture of PE materials with a wider range of properties, thus giving a wider scope for analysis. This is covered later in this chapter under the heading of alloying.

## 6.4 Addition of talcum particles

### 6.4.1 Tensile testing results

Figure 6.17 shows the percentage change in UTS with increasing concentrations of talcum. The results show different responses from the two materials, but it should be noted that the magnitudes of these overall changes are comparatively small.

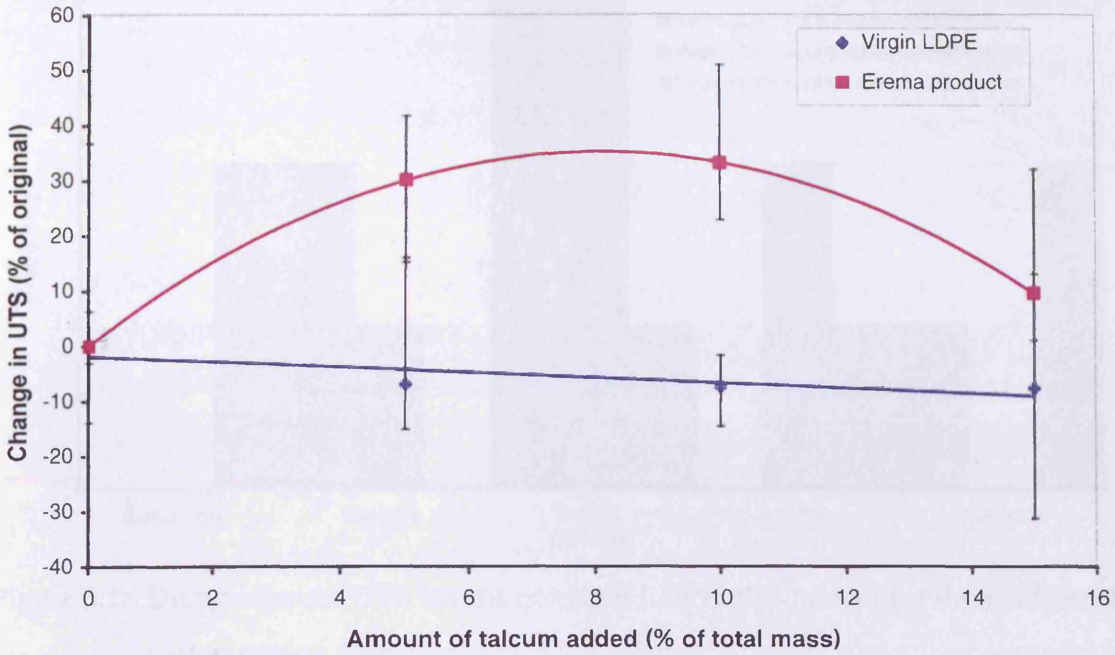


Figure 6.17 The percentage change in UTS of two different polymers with talcum addition.

It can be seen that the addition of talcum-like contamination seems to have little significant impact on the UTS of the virgin LDPE up to 15% contamination, which would be a realistic maximum in a practical sorting and cleaning operation. The decrease in UTS follows a linear relationship of around 6% per 10% talcum contamination. For the Erema material the change was more significant with an increase up to a maximum of 30% of the original UTS. At 15% contamination the UTS change is less, with an increase of 10% of the original value.

The UTS value at 15% talcum contamination for the virgin LDPE showed a larger range than expected in the data used to make the averaged point. This data was therefore studied to examine the distribution of the data at this point. Figure 6.18 shows the distribution of the data over five quintiles for three different contamination levels. The data at 15% talcum contamination did not have a normal distribution, unlike the data distributions in the 5% and 10% levels, used as a comparison. This was another case where more data used to average the result would help determine a more accurate value for the UTS, but as highlighted earlier it was assumed that this parameter is not crucial in the overall analysis.

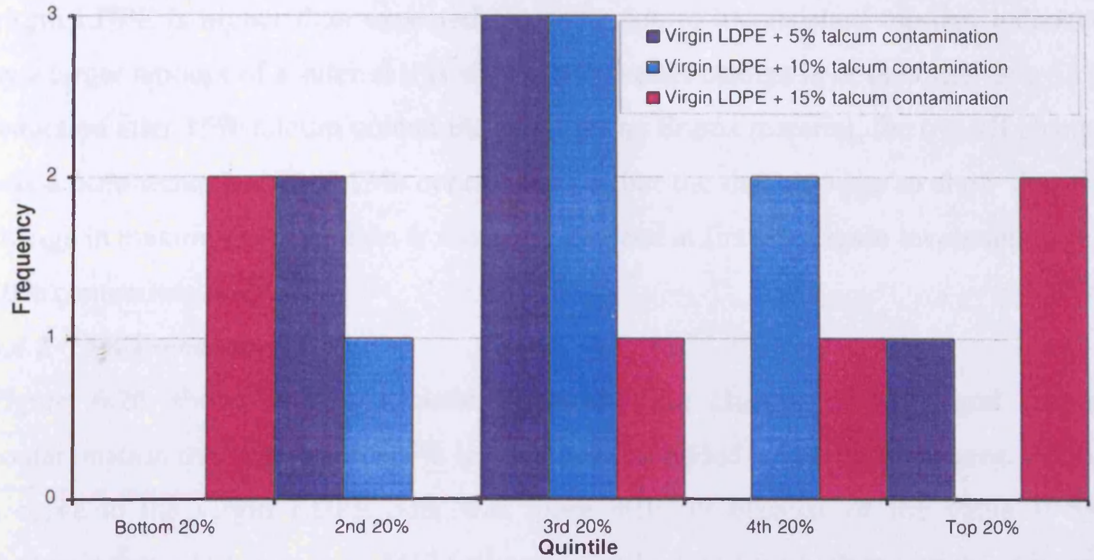


Figure 6.18 Distribution of UTS results of virgin LDPE plus talcum for three different contamination levels.

Figure 6.19 shows the variation of maximum elongation as a percentage of the original value with increasing amounts of talcum. The magnitude of the change in maximum elongation is greater than the change in the UTS for the same levels of contamination.

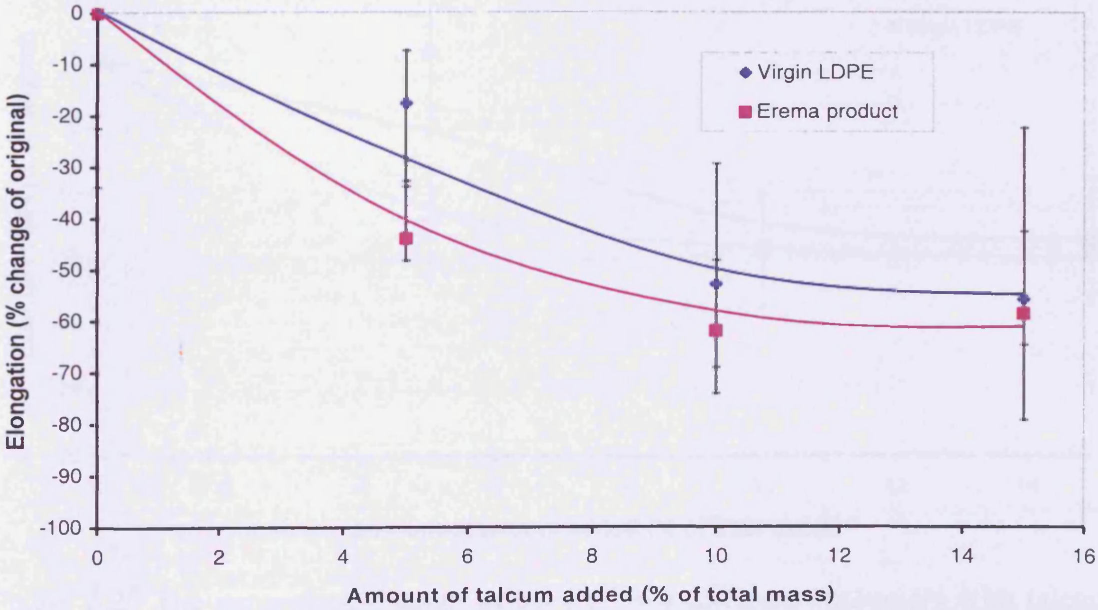


Figure 6.19 The percentage change in maximum elongation of two different polymers with talcum addition

A best fit curve was applied to both sets of data to show the overall trend. In both material cases, the talcum contamination over the 0% to 15% range appears to reach a minimum value after 10% contamination. The data point at 5% contamination for virgin LDPE is higher than expected, possibly due to inconsistent mixing, indicated by a larger amount of scatter at this value. The overall change is of the order of a 55% reduction after 15% talcum contamination. For the Erema material, the overall change was a 60% reduction after 15% contamination, but the data appears to show that the change in maximum elongation is more pronounced at first and again levels-out above 10% contamination.

### 6.4.2 MFI measurement.

Figure 6.20 shows the relationship between the change in MFI and talcum contamination over the 0% to 15% level of talcum added to the two mixtures. Fitting a curve to the virgin LDPE data was more difficult because of the value at 5% contamination. The change in MFI follows a similar trend for both materials, although there appears to be an anomaly at 5% contamination with the virgin LDPE. As the value was similar to the original value at 0% contamination it could be due to either a sample with a much lower talcum concentration than expected or the contamination having no effect until a higher threshold value was reached.

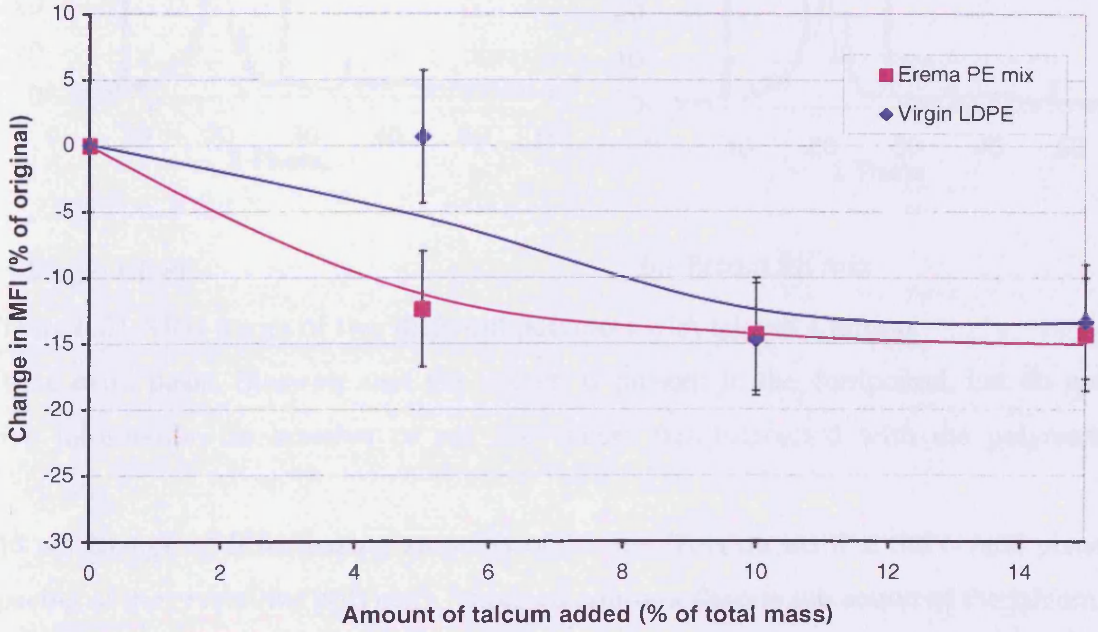
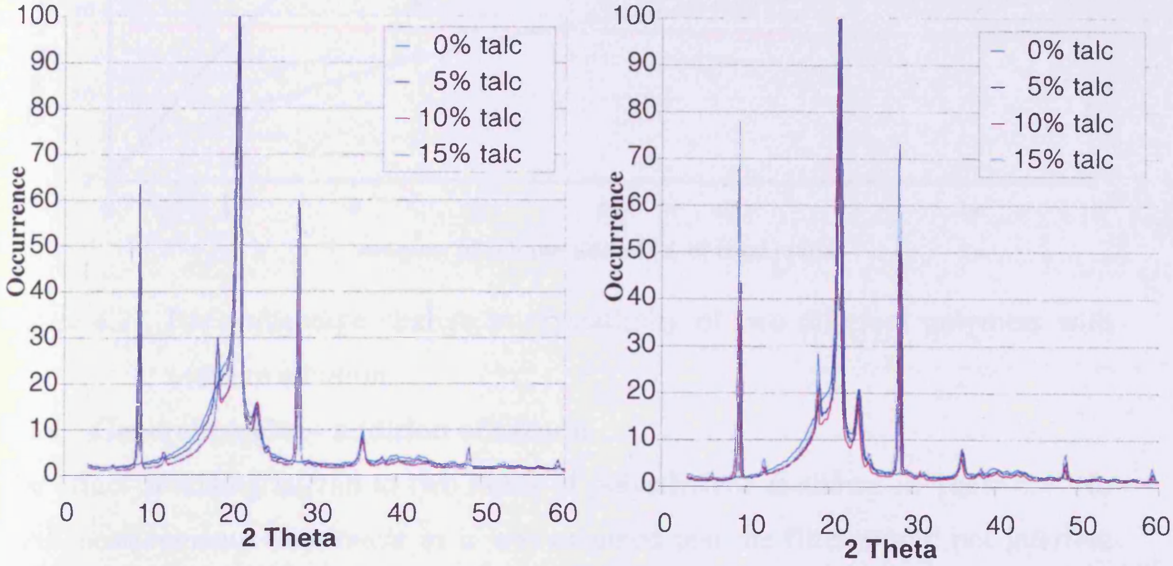


Figure 6.20 The percentage change in MFI of two different polymers with talcum addition.

Despite the difference of 0.5 g/10min in MFI between the two PE materials examined, the decrease in MFI was around 6% per 1% talcum addition in both cases. It is logical to assume that these changes would be due to a fairly simple relationship because the talcum is acting to increase the viscosity of the material. Thus the amount of talcum added should have a direct effect on the change in MFI. The index is a far more important property during manufacture, thus dirt contamination is more detrimental during the processing stage than its effect on the end product.

### 6.4.3 XRD measurements

Figure 6.21 shows the XRD results for the talcum addition studies. The sharp peaks at $2\theta$ values of 9.26°, 18.74° and 28.37° were identified as a talcum compound with the chemical formula $Mg_3Si_2O_{10}(OH)_2$ using the a crystal salt database with the XRD software.



a.) Virgin LDPE b.) Erema PE mix

Figure 6.21 XRD traces of two different polymers with talcum addition.

These extra peaks illustrate that the talcum is present in the compound, but do not give information on whether or not the talcum has interacted with the polymers

did not change with increasing amounts of talcum. This means that the crystal plane spacing of the crystalline polymers remained constant despite the action of the talcum. It is therefore logical to assume that on a crystalline level, the talcum has virtually no effect of the polymer chains and their alignment, but it merely ‘sits around’ them.

Figure 6.22 shows the change in crystallinity with amount of talcum added to the polymers, with best-fit curves through the data sets. This data showed that there was a steady increase of about 10% crystallinity per 10% talcum added, however the scatter suggests that the talcum was not uniformly distributed around the bulk of the material.

Similarly for the MFI results, the changes were more pronounced over the 0% to 10% contamination range.

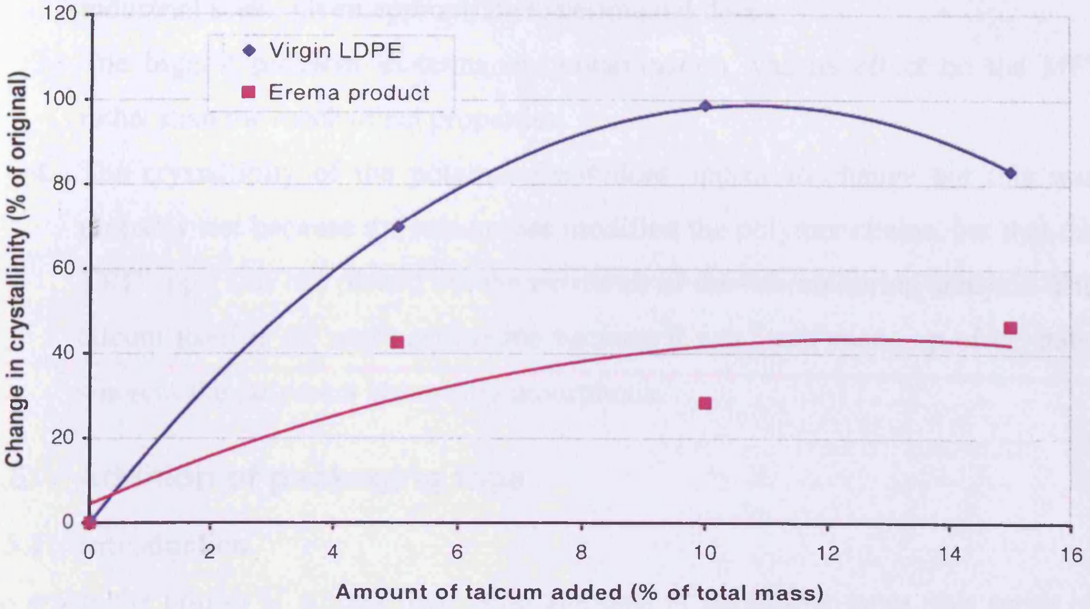


Figure 6.22 The percentage change in crystallinity of two different polymers with talcum addition.

### 6.4.4 General results – addition of talcum

The effect of adding talcum to two kinds of polyethylene is shown in Table 6.4. No GPC measurements were made as it was assumed that the filler would not interfere with the molecular structure of the polymer chains and as such there was little point in looking at the polymer molecular masses.

Table 6.4 Adding talcum to LDPE

| Material | UTS | % Elong. | MFI | Crystallinity | MWT dist. |
|---|---|---|---|---|---|
| Virgin LDPE | Decreased | Decreased | Decreased | Increased | - |
| Erema PE mixture | Increased | Decreased | Decreased | Increased | - |

The following overall observations can be made about adding talcum contamination:

1. Increasing the amount of talcum made the material stiffer (i.e. an increase in Young's modulus) and stiffness changes were sufficiently consistent such that they can be modelled using this experimental data.

2. Increasing the amount of talcum made the materials inherently more viscous and thus harder to process, this would also be simple to quantify on an industrial scale, given appropriate experimental data.
3. The biggest problem in terms of contamination was its effect on the MFI rather than the mechanical properties.
4. The crystallinity of the polymer itself does appear to change but this was probably not because the talcum has modified the polymer chains, but that the XRD apparatus has picked out the existence of the talcum during analysis. The talcum itself is far more crystalline because it was itself made up of crystals, whereas the polymers are mostly amorphous.

## 6.5 Addition of packaging tape

### 6.5.1 Introduction

To assess the impact of adding increasing amounts of packaging tapes, this series of experiments used three varieties of tape: Polypropylene (parcel packaging) tape, cellulose based tape (commonly known as cellotape) and PVC tape (sometimes called insulation tape). The three were chosen as they are examples of commonly used varieties of tape found with polyethylene film applications.

### 6.5.2 Tensile testing

Figure 6.23 shows the effect of adding the tapes to polyethylene film material.

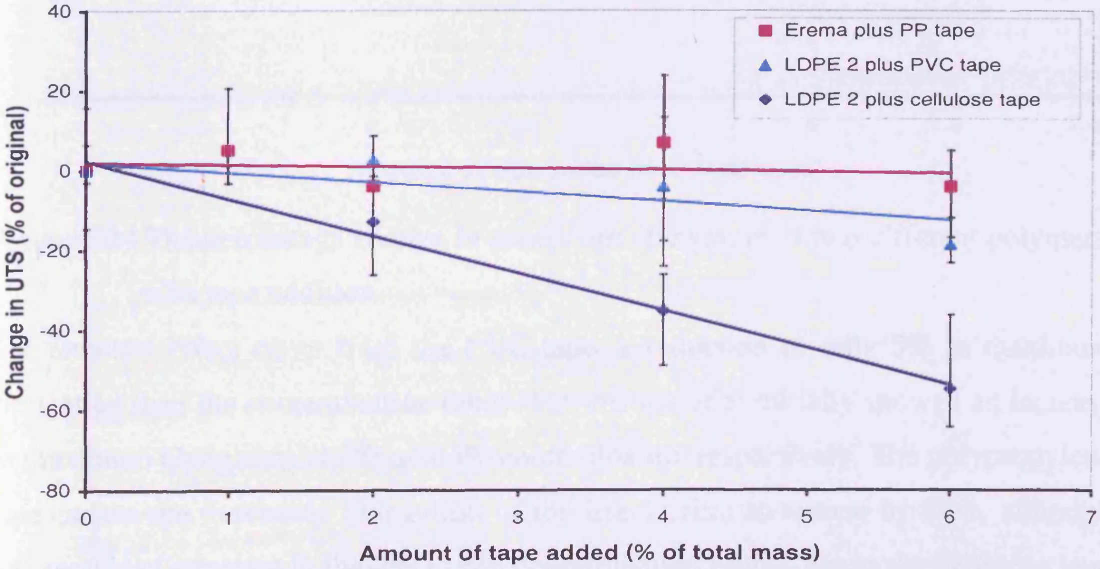


Figure 6.23 The percentage change in UTS of two different polymers with tape addition.

There were two types of PE film used, namely the recycled Erema PE mix and broad-spec LDPE. In each case the UTS was reduced, expressed with a linear trendline through the data. The data shows that the polypropylene tape had the smallest effect on the material over the range studied, with only a 1% reduction in UTS up to 6% tape contamination. The PVC tape caused a decrease of 15%, from its original value of 29.5 MPa. The cellulose based tape had the most detrimental effect of a reduction of 55% over the 0% to 6% contamination range.

Figure 6.24 Shows the effect the tape has on the plastic film in terms of the change in maximum elongation, with best-fit curves applied to the data sets. In all three cases the tape caused a reduction in the maximum elongation.

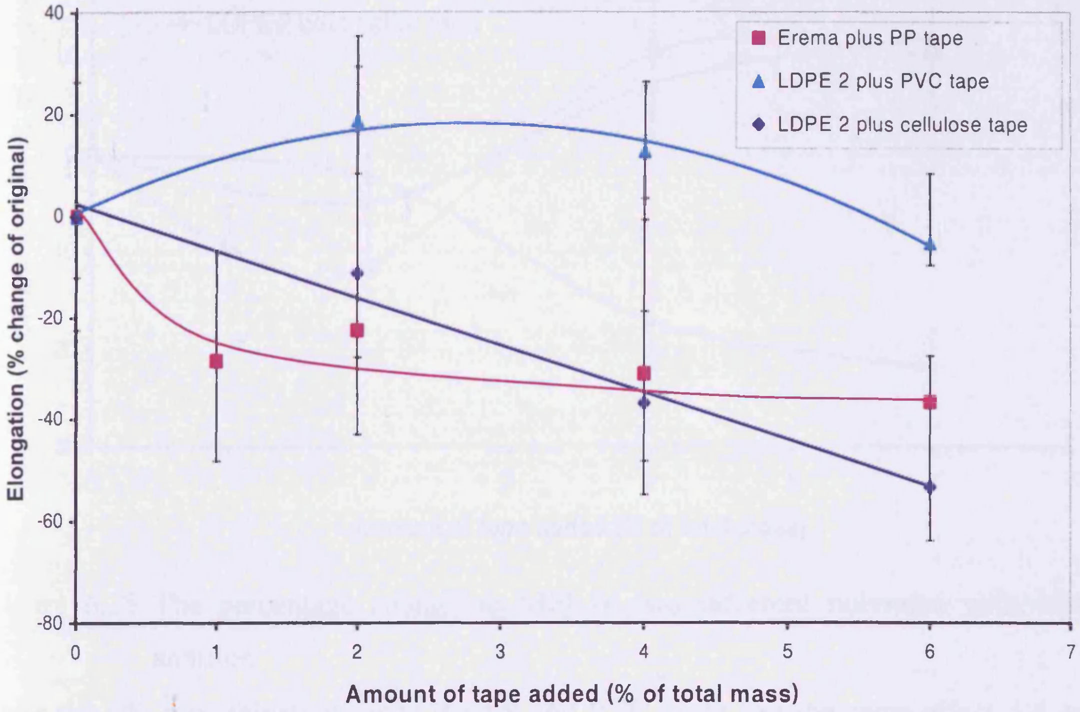


Figure 6.24 The percentage change in maximum elongation of two different polymers with tape addition.

The smallest effect came from the PVC tape, a reduction of only 5% in maximum elongation over the contamination range, but this material initially showed an increase in maximum elongation at 2% and 4% contamination respectively. The polypropylene tape caused the maximum elongation of the Erema film to reduce by 37%, although this remained constant in the 4% to 6% contamination range. Again the cellulose tape had the most detrimental effect, causing the maximum elongation to reduce by 53% over the range of the test. This shows that the tapes were affecting mechanical properties differently, depending on the type of tape used and that the cellulose tape contamination has the largest (and most weakening) effect on the tensile properties examined.

### 6.5.3 MFI measurement

Figure 6.25 shows the change in MFI with increasing amounts of packing tape. The data shows that the cellulose tape had the opposite effect than that of the polypropylene and PVC tapes, causing a decrease in viscosity rather than an increase. This was due to the cellulose tape having a much lower MFI than the PE materials.

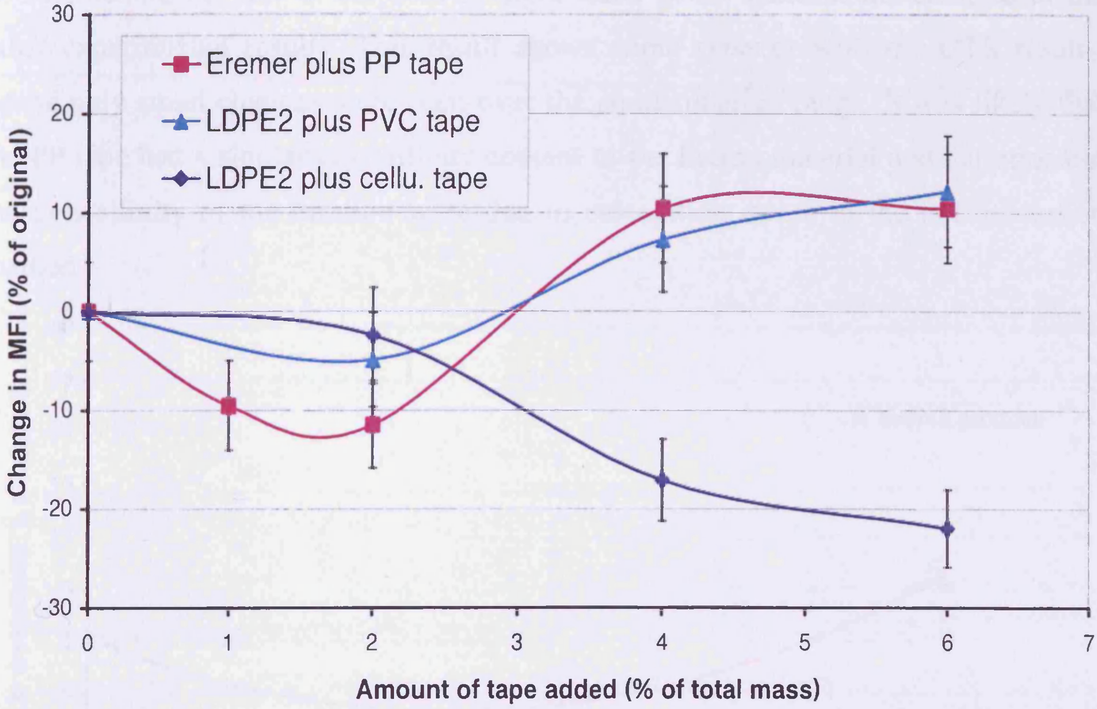


Figure 6.25 The percentage change in MFI of two different polymers with tape addition.

Over the 6% contamination range the PP and PVC tapes had the same effect, i.e. to increase the original MFI value by 12%. There was more scatter in the Erema / PP tape data, probably due to inconsistent mixing. Qualitatively it can be seen that the effects of the PP and PVC tapes are similar, despite using different PE materials for the study. The effect of the cellulose based tape was the largest and shows a reduction in MFI, i.e. an increase in melt viscosity, which would make manufacturing the contaminated material more difficult. This relationship showed a decrease of 22% from its original value over the 6% contamination range.

### 6.5.4 XRD measurements

Only the Erema product with PP tape was tested for this study. Initially the crystallinity decreased at 2% contamination but steadily increased thereafter over the range tested. It was interesting to note that three of the five data points show no change from the original crystallinity value at 0% contamination.

Figure 6.26 shows the effect of adding PP tape to the Erema mixture. There was perhaps a small overall increase in crystallinity of about 5% over the range of contamination, but this is not seen as significant, given some of the changes in the other experimental results. This result shows some synergy with the UTS results, where only small changes were seen over the contamination range. It was likely that the PP tape had a similar crystallinity content to the Erema material and variations in the crystallinity of the mixture were due to calculation errors in the deconvolution method.

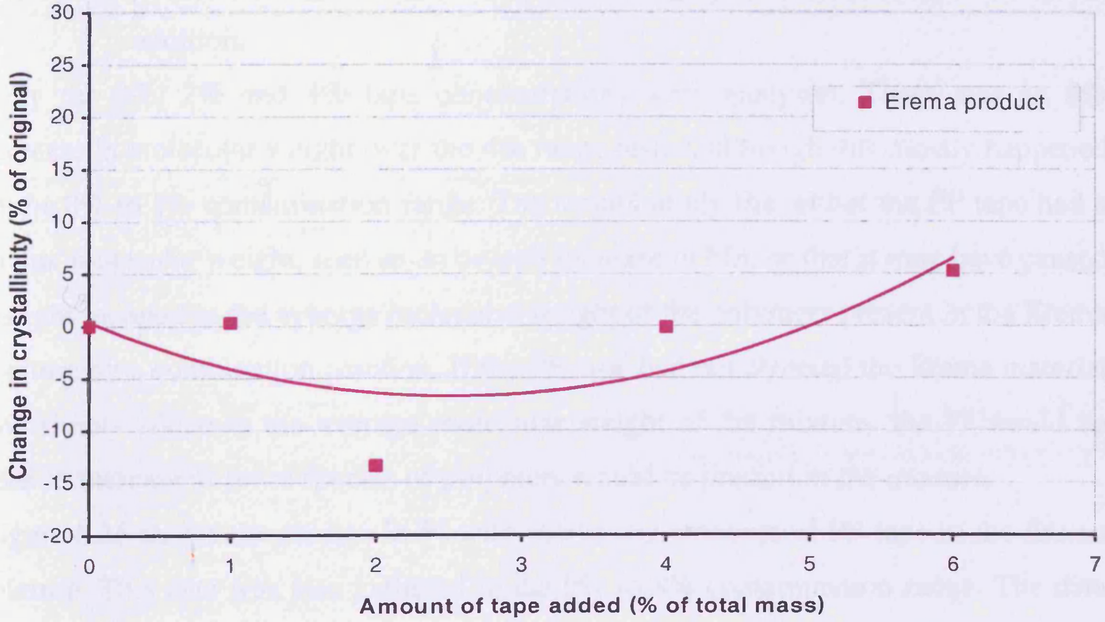


Figure 6.26 The percentage change in crystallinity of Erema product with tape addition.

### 6.5.5 GPC results

Figure 6.27 Shows the relationship between the molecular weight by number (Mn) with increasing amounts of packaging tape added to the Erema PE mixture. A best-fit curve has been used to show the trend.

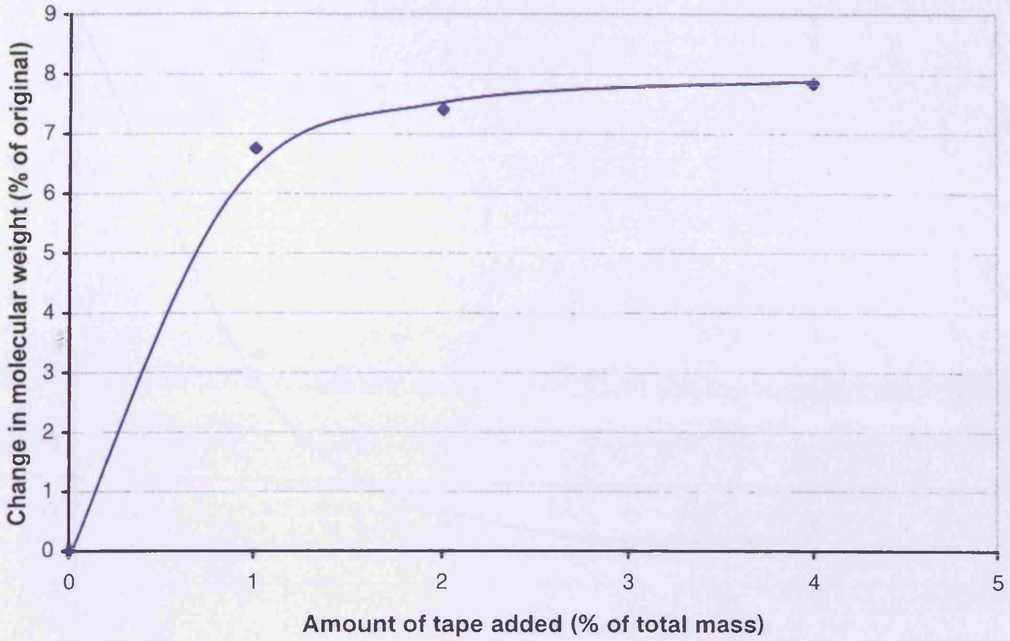


Figure 6.27 The percentage change in molecular weight of Erema product with tape addition.

Only the 0%, 2% and 4% tape concentrations were analysed. There was an 8% increase in molecular weight over the 4% range tested, although this mostly happened in the 0% to 1% contamination range. The results imply that either the PP tape had a higher molecular weight, seen as an overall increase in Mn, or that it may have caused a slight increase in the average molecular weight of the polymers present in the Erema mixture by a combination reaction. If the PP tape had not affected the Erema material and simply added to the average molecular weight of the mixture, the PI would be seen to increase as more species of polymers would be present in the mixture.

Figure 6.28 shows the change in PI with increasing amounts of PP tape in the Erema mixture. This data was also gathered in the 0% to 4% contamination range. The data shows that the PI decreased steadily by 7% with up to 2% tape contamination and remained constant up to 4% contamination. This implies that the mixture was less varied in its composition with increasing amounts of tape contamination. Coupled with the increase in molecular weight from Figure 6.27, there appears to be an interaction between the tape and the polyethylene, causing an increase in the population of the higher molecular weight species of polymer and a decrease in the population of the lower molecular weight polymer. This was plausible given that the PP tape is predominantly made from a polymer with a similar structure to the LDPE material.

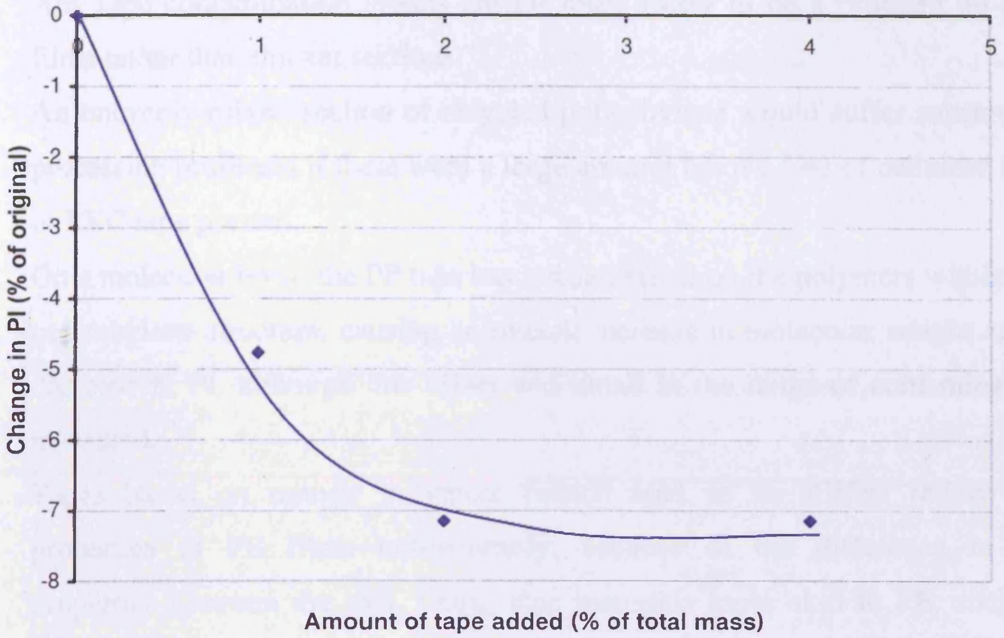


Figure 6.28 The percentage change in PI of Erema mixture with PP tape addition.

### 6.5.6 General results – tape addition

The effect of adding tape to the polyethylene is shown in Table 6.5.

Table 6.5 Adding packaging tapes to polyethylene.

| Material | UTS | % Elong. | MFI | Crystallinity | PI |
|---|---|---|---|---|---|
| Erema PE mixture | Decreased | Decreased | Increased | Increased | Decreased |
| "broad-spec" LDPE | Decreased | Decreased | Increased, but decreased with cellulose tape | - | - |

The following observations can be made about adding packaging tape to polyethylene materials :

1. The effect to which a tape changes the tensile and MFI properties was very much dependent on the type of tape material that has been added.
2. Cellulose based tapes have the most detrimental effect on the material properties of those tapes tested. Packaging tapes have minimal effects under the concentrations tested.
3. Crystallinity was slightly increased by adding packaging tape.

4. Any tape contamination effects are far more likely to be a problem on thin films rather than thicker sections.
5. An unevenly-mixed section of recycled polyethylene would suffer substantial processing problems if there were a large amount (above 6%) of cellulose tape or PVC tape present.
6. On a molecular level, the PP tape has a small effect on the polymers within the polyethylene structure, causing an overall increase in molecular weight and a decrease in PI, although this effect was small in the range of contamination measured.
7. Tapes based on natural polymers (which tend to be stiffer) reduce the properties of PE films unfavourably, because of the difference in the properties between the two. Using tape materials more akin to PE, such as polypropylene will give a resultant mix which retains most of its mechanical properties.

## 6.6 Addition of finely mixed contamination

### 6.6.1 Tensile testing

The materials used in this experiment were:

- Broad spec LDPE – a blended mixture of LDPE materials for packaging specification, with an MFI of around 0.45 g/10min.
- Black masterbatch LDPE – a heavily dyed virgin LDPE that is added to LDPE feedstocks in order to change its colour and mechanical properties, comprising of 66% calcite filler additives by mass, supplied by Centriforce Products Ltd. For more details of masterbatching see Section 3.8.1. The MFI of this calcite / PE mixture was 0.14 g/10min.

Figure 6.29 shows the change in UTS with increasing amounts of finely mixed contamination. It was evident that the masterbatch caused a reduction in UTS. A best fit curve has been applied to the data.

The figure shows that there was a decrease in UTS of 34% over the range of the added contamination, with an average decrease of 5% per 10% filler. Although the trend line shows a decrease in UTS, when considering an individual data point, say the 5% calcite filler addition, it indicates a slight increase in UTS of about 5%. Initially the dye agent was acting as a stiffener by increasing Young's Modulus. Further addition of the filler weakened the material and hence showing a loss in strength. This observation was similar to that seen when using a combination of talcum with LDPE and the Erema mixture as previously discussed.

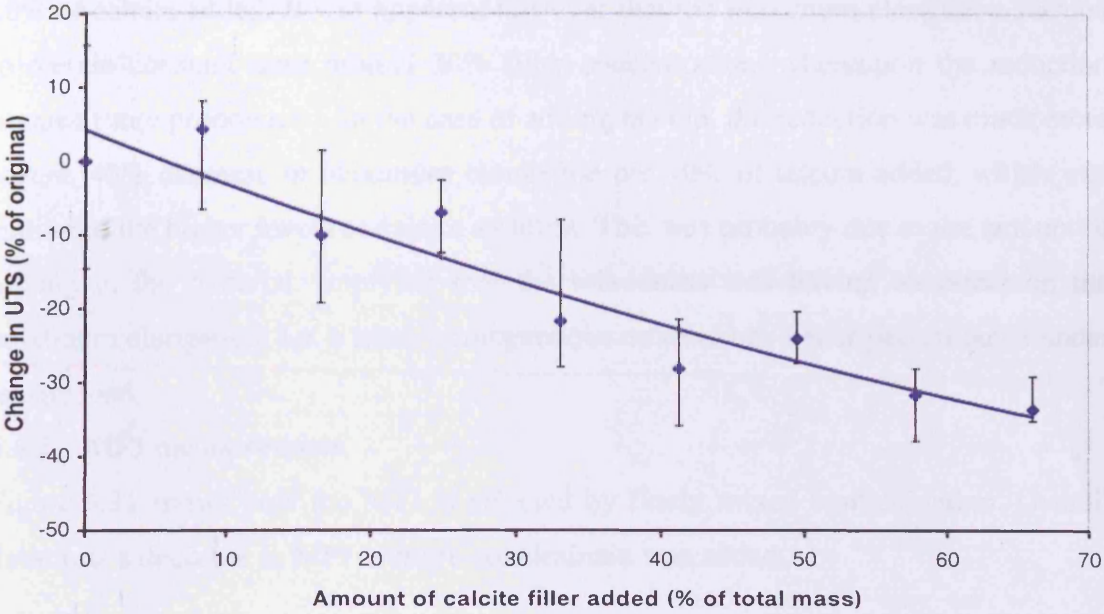


Figure 6.29 The percentage change in UTS of LDPE with calcite filler addition.

Figure 6.30 shows the change in maximum elongation as a function of calcite contamination. The relationship was not as straightforward as in the UTS experimental data. A best fit curve has been used again on the data, and was configured to show the maxima at 10% calcite filler.

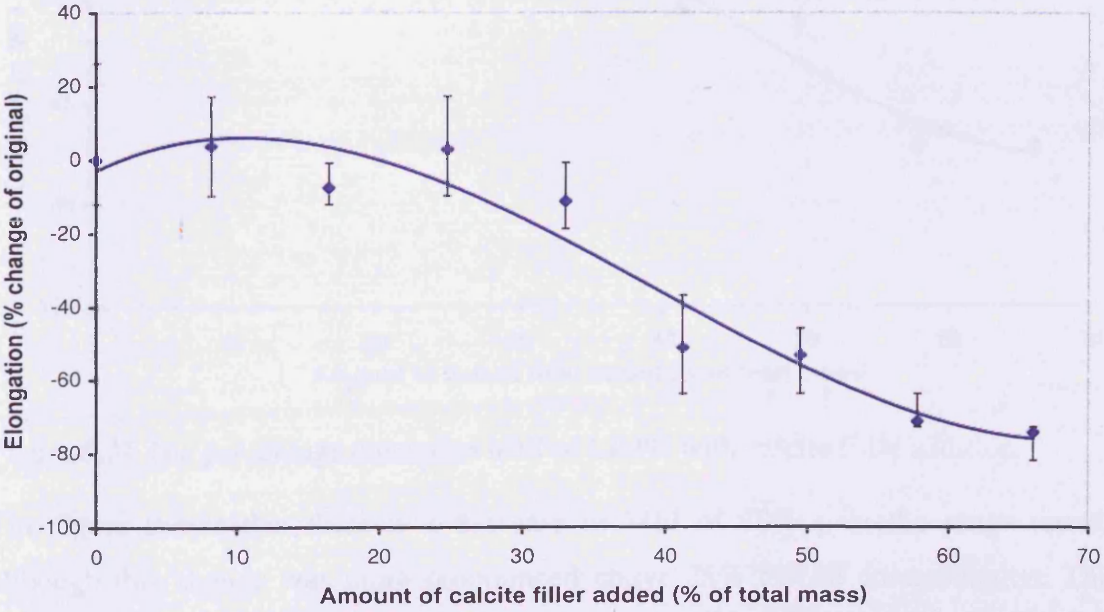


Figure 6.30 The percentage change in maximum elongation of LDPE with calcite filler addition.

The figure shows that there is a decrease in maximum elongation of 76% over the range tested, with an average decrease of 12% change in maximum elongation per 10% of calcite added. It was apparent however that the maximum elongation seemed to remain constant until around 30% filler concentration, whereupon the reduction became more pronounced. In the case of adding talcum, the reduction was much more severe, 40% decrease in maximum elongation per 10% of talcum added, which was similar to the higher levels of calcite addition. This was probably due to the amount of mixing in the material, implying that the mixedness was having an effect on the maximum elongation, i.e. a more homogeneous mixture has better performance under tensile load.

### 6.6.2 MFI measurement.

Figure 6.31 shows how the MFI is affected by finely mixed contamination. Overall there was a decrease in MFI as more contaminant was added.

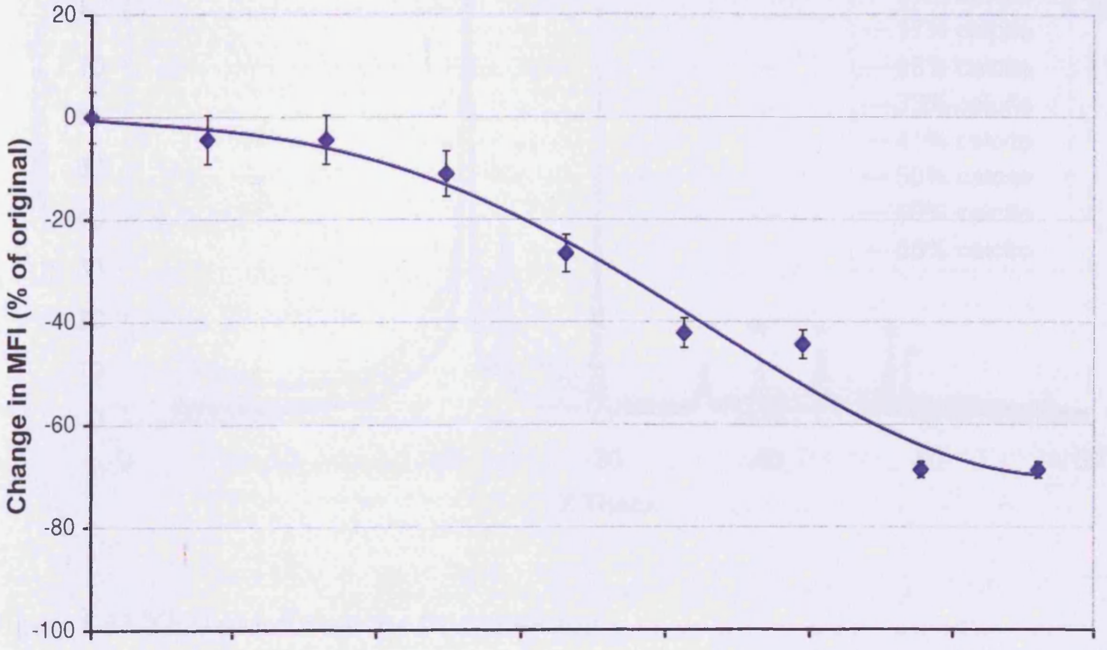


Figure 6.31 The percentage change in MFI of LDPE with calcite filler addition.

The figure shows that there is a decrease in MFI of 70% over the range tested, although this change was more pronounced above 25% calcite contamination. The higher amounts of contamination deviate slightly from the curve, which was probably due to the carrier polyethylene that the calcite additive was suspended in. This polymer was slightly different to the broad spec LDPE that was used for the experiment. Homogeneity was not such a problem in the case of MFI testing because the tests were averaged over a large time period and shown to be consistent within 5% of the mean of every other test point.

### 6.6.3 XRD measurement

Figure 6.32 shows the XRD trace for the study. Unlike many of the other results the relationship was much clearer because the materials being mixed together (semi-crystalline polymer and amorphous dye) are more different than mixing similar polymers. The peaks indicated on the figure with a star correspond to the additional features not normally expected on an XRD trace for polyethylene. After further analysis with the XRD material database software it was found that they most likely correspond to a calcite compound, i.e. that the additive was calcite based.

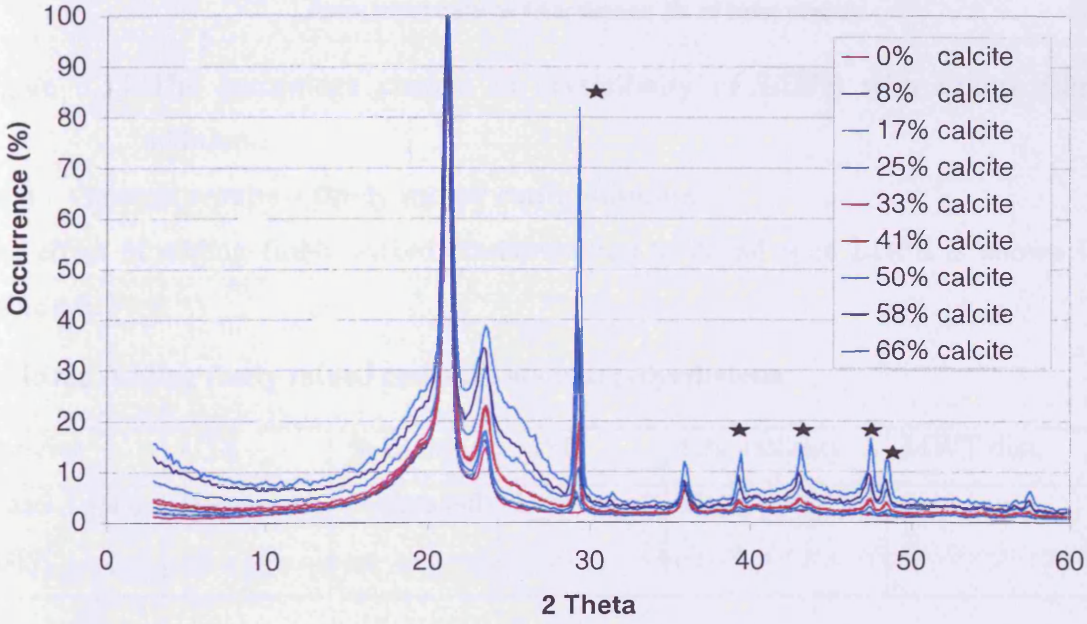


Figure 6.32 XRD plot for calcite filler addition

Figure 6.33 shows the change in calculated crystallinity of the LDPE when mixed with the calcite contaminant. The response showed a small amount of scatter as the amount of calcite is increased.

There was a decrease of about 3.7% crystallinity per 10% calcite addition. This was contrary to the observations made when adding talcum to the material, which showed an increase in crystallinity over the range tested (0% to 15% contaminant by mass) although this could be due to the carrier PE that the calcite was suspended in.

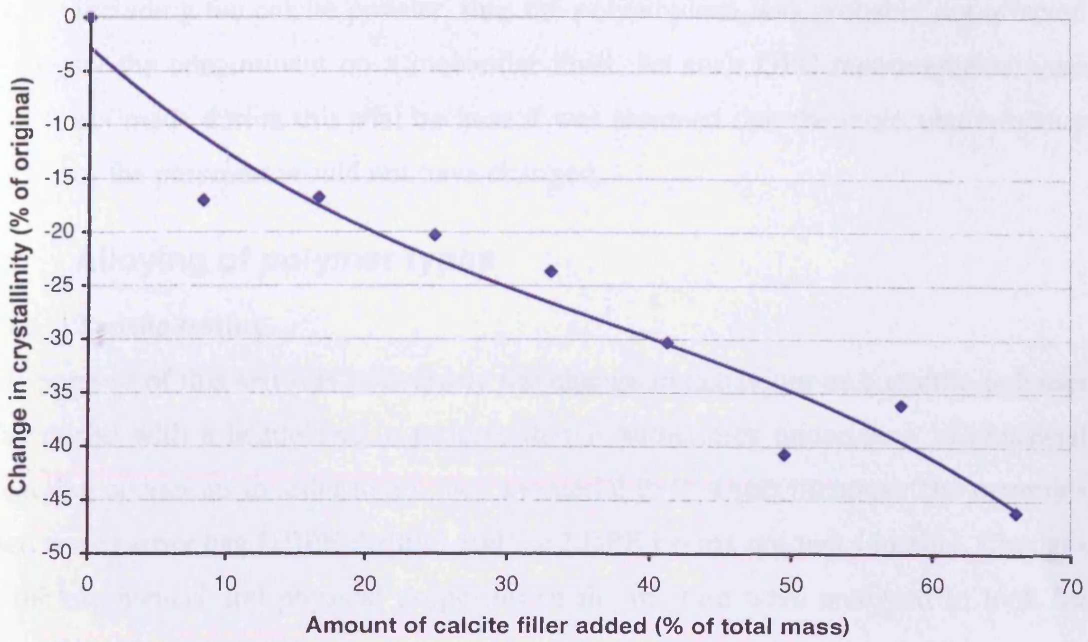


Figure 6.33 The percentage change in crystallinity of LDPE with calcite filler addition.

### 6.6.4 General results – finely mixed contamination

The effect of adding finely mixed contamination to broad spec LDPE is shown in Table 6.6.

Table 6.6 Adding finely mixed contamination to polyethylene.

| Material | UTS | % Elong. | MFI | Crystallinity | MWT dist. |
|---|---|---|---|---|---|
| Broad spec. LDPE | Decreased | Decreased | Decreased | Decreased | - |

The following overall observations were made when adding finely mixed contamination to PE:

1. Increasing amounts of finely mixed contamination decreased both the UTS and maximum elongation, although some stiffening occurred at lower contamination levels.
2. As with the talcum contamination, the contaminant made the material more viscous and thus decreased the MFI, the relationship was fairly simple and could be modelled based on experimental results.
3. Although a change in crystallinity was measured, it was assumed that this was due to the XRD apparatus measuring the crystallinity of the whole mixture,

including the calcite powder, thus the polyethylene was probably not affected by the contaminant on a molecular level. As such GPC measurements were not made during this trial because it was assumed that the molecular structure of the polymers would not have changed.

## 6.7 Alloying of polymer types

### 6.7.1 Tensile testing

The purpose of this test was to evaluate the change in behaviour as a ductile polymer was mixed with a brittle one, a process that is sometimes undertaken in industrial recycling operations in order to produce a material to fit a specification. The materials used were carrier bag HDPE (brittle) and the LDPE Erema product (ductile). Changes in the mechanical and physical properties of the mixture were analysed to look for correlations in mixing behaviour.

Figure 6.34 shows the percentage change in UTS as the carrier bag HDPE film was mixed with increasing amounts of the Erema mixture. A best-fit curve was put through the data. There was a decrease in UTS with increasing amounts of Erema product in the mixture.

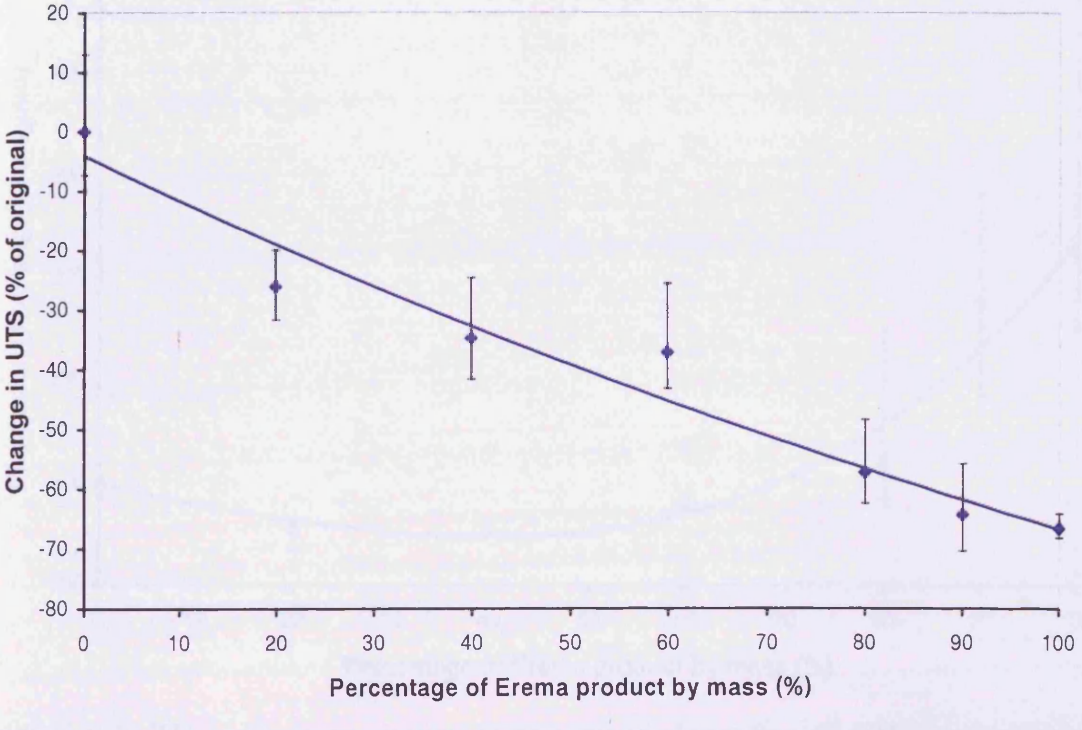


Figure 6.34 The percentage change in UTS of HDPE with Erema mixture addition.

It can be seen that there was a decrease in UTS of 67% throughout the range of the test. This was the difference between the UTS of both materials, i.e. from the HDPE to the Erema mixture. Although the trend appears almost linear, a second-order trendline was drawn through the data with a minimal amount of scatter. It was therefore apparent that the relationship between change in composition and change in UTS was straightforward, but not in direct proportion to the composition.

Figure 6.35 shows the change in maximum elongation and composition for the alloyed materials. It can be seen that the relationship was different to that of the UTS case. The maximum elongation of the mixture stayed constant until a mixture ratio of 60% Erema material. From this point the elongation increased by 230% over the remaining mixture range. Also visible was the increase in the range of the data at 80%, 90%, and 100% Erema concentration, this being consistent with the range normally seen for this material. The figure shows that there is a different relationship between UTS and maximum elongation when alloying polymers. The larger values for the error bars at the 80% - 100% composition values are due to the fact that the Erema material was far more varied in composition and therefore more likely to have a larger variance compared to the HDPE material, which was more homogeneous in composition.

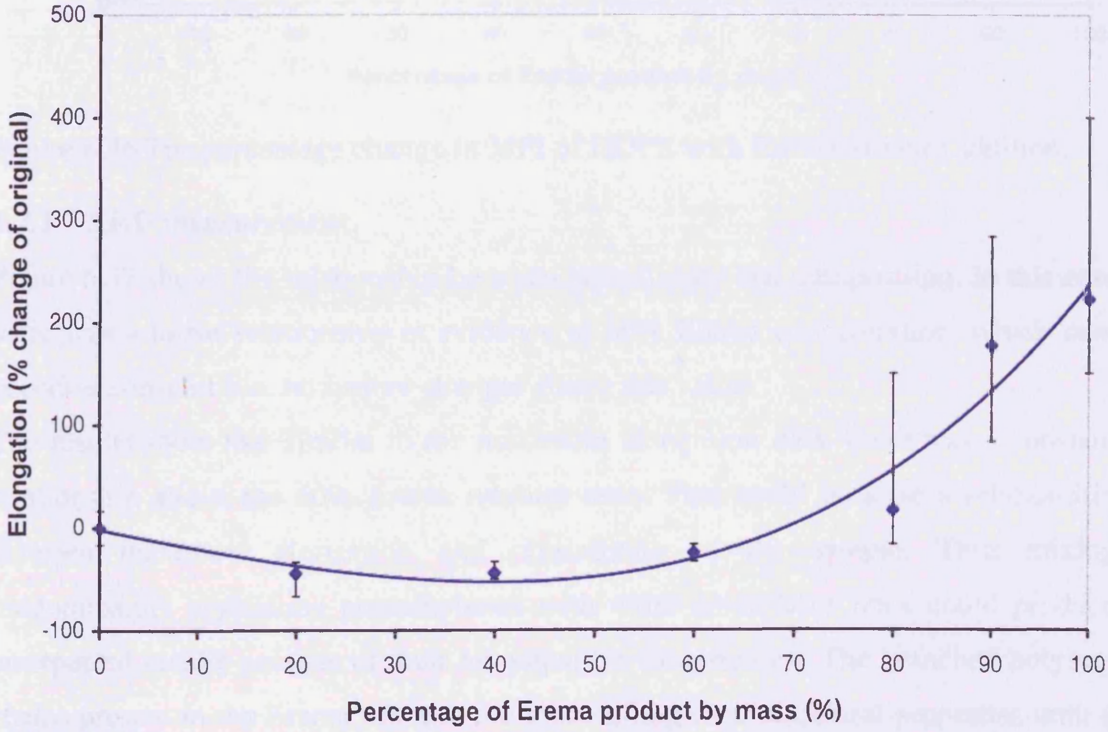


Figure 6.35 The percentage change in maximum elongation of HDPE with Erema mixture addition.

### 6.7.2 MFI measurement

Figure 6.36 shows the relationship between the MFI and the composition of the blend. There was an increase in MFI of about 780%. It was evident that the alloying of polyethylenes produces a steady change in MFI. If processing of a material is of chief concern, then alloying mixtures together is a matter of using two materials in direct proportion to the intended MFI of their product.

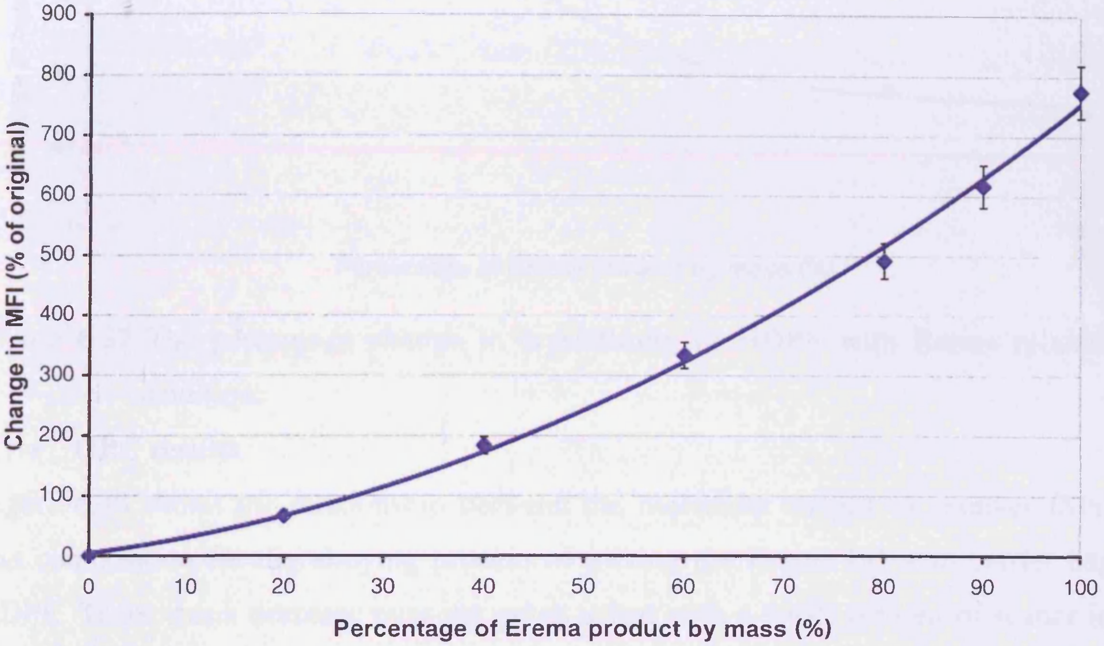


Figure 6.36 The percentage change in MFI of HDPE with Erema mixture addition.

### 6.7.3 XRD measurement

Figure 6.37 shows the relationship between crystallinity and composition. In this case there was a linear relationship in evidence to 60% Erema concentration, which then becomes constant (i.e. no further change) above this value.

The results show that similar to the maximum elongation data, there was a constant relationship above the 60% Erema mixture ratio. This could indicate a relationship between maximum elongation and crystallinity of the sample. Thus mixing predominantly crystalline polyethylenes with more amorphous ones could produce unexpected results because of their incompatible morphology. The branched polymer chains present in the Erema mixture are maintaining their structural properties until a saturation of HDPE occurs, sufficient to dominate the overall structure. This saturation appears to be at around 60% carrier bag HDPE in this particular mixture.

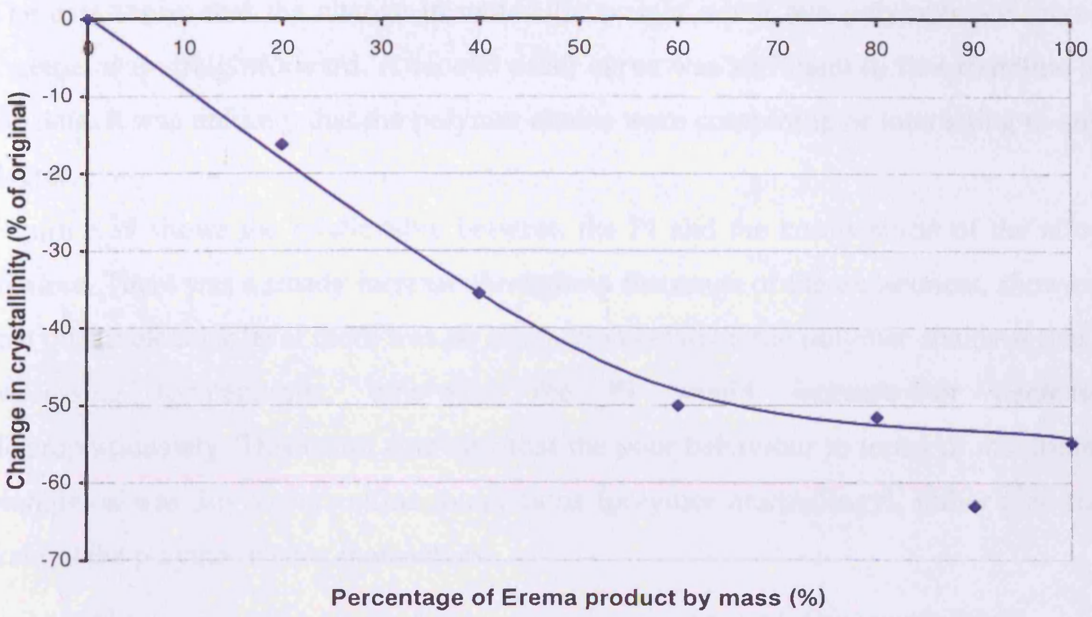


Figure 6.37 The percentage change in crystallinity of HDPE with Erema mixture addition.

### 6.7.4 GPC results

Figure 6.38 shows the relationship between the molecular weight by number (Mn) and composition for the alloying process of mixing the Erema PE with carrier bag HDPE. There was a decrease over the range tested with a small amount of scatter in the data.

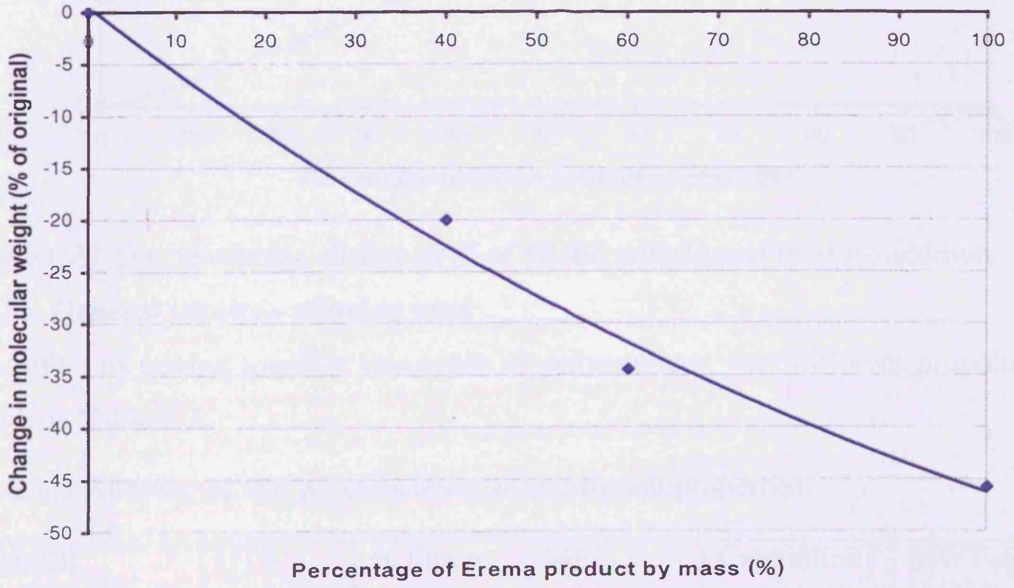


Figure 6.38 The percentage change in molecular weight of HDPE with Erema mixture addition.

The data shows that the change in molecular weight when two polymers are mixed together was straightforward. A second order curve was sufficient to fit a trendline to the data. It was unlikely that the polymer chains were combining or interacting to any degree.

Figure 6.39 shows the relationship between the PI and the composition of the alloy mixture. There was a steady increase throughout the range of the experiment, showing that on a molecular level there was no interaction between the polymer chains at these processing temperatures, otherwise the PI would increase or decrease disproportionately. This result confirms that the poor behaviour in terms of maximum elongation was due to crystalline interactions (polymer morphology), rather than the state of the polymer chains themselves.

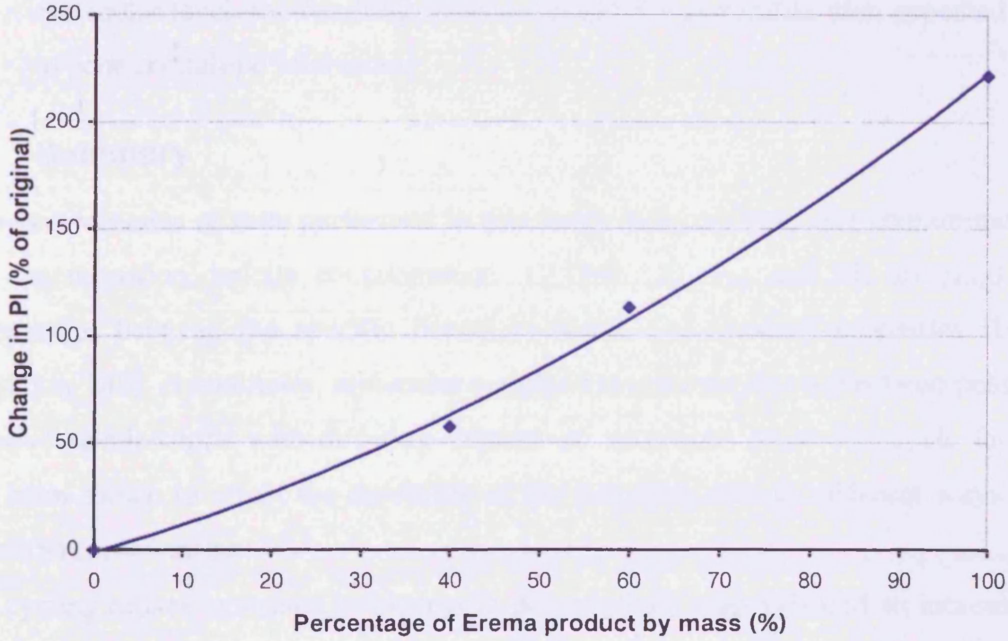


Figure 6.39 The percentage change in PI of HDPE with Erema mixture addition.

### 6.7.5 General results – alloying tests

The effect of mixing together two types of polyethylene with different properties if shown in Table 6.7.

Table 6.7 Alloying of two polyethylenes with different properties.

| Material | UTS | % Elong. | MFI | Crystallinity | MWT dist. |
|---|---|---|---|---|---|
| Erema PE mixture plus Carrier bag HDPE | Decreased | Increased | Increased | Decreased | Added via superposition |

The following overall observations can be made about the alloying of PE:

1. Mixing two polyethylenes together was dependent on their morphology.
2. UTS changes would be straightforward to model.
3. Maximum Elongation changes are non-linear and correlate with changes in crystallinity
4. MFI changes would be straightforward to model.
5. Mixing branched and un-branched polymers simply results in a mixture with an average molecular weight and polydispersity that is dependent on the material fraction, i.e. the change is linear with respect to mass fraction.
6. Polyethylenes will not always combine favourably in a mixture if they are from different feedstocks. Although there was no significant interaction on a molecular level, the resulting mixture could be less flexible than expected due to poor crystalline interaction.

## 6.8 Summary

Of the six varieties of tests performed in this study (heat cycling, dirt contamination, tape contamination, calcite contamination, LLDPE alloying and PE alloying) the relationships between the specific life-cycle factor and material properties (UTS, elongation, MFI, crystallinity, molecular weight) have shown that it has been possible to derive relationships with differing degrees of accuracy. These life-cycle factors have been shown to affect the durability of the polyethylenes in different ways and with different severities.

Heat cycling causes increased brittleness in polyethylene materials and an increase in melt viscosity. Morphology of the material blend has an impact on how it behaves under thermal cycling, amorphous materials become more crystalline, whereas crystalline materials become more amorphous. In all cases there was a decrease in mean molecular mass and a small increase in PI.

Polyethylene materials treated with dirt-like contamination become stiffer at first, but then reduce as the contaminant is increased. Melt viscosity also increases, but it was unlikely that any morphological or molecular properties are altered as the contaminant does not interact with the polymer chains. The mixedness of the contaminant also has a marked effect on the resultant material properties. Highly-mixed materials are stronger and have larger maximum elongation values.

Polyethylene materials mixed with packaging tapes have properties that are dependent on the type of tape used, for example cellulose-based tapes make the resultant mixture brittle and less viscous in the melt state. From the work covered in this study, polypropylene tapes are the most favourable in terms of contamination, because the structure of PP and PE are similar, so the resultant material has properties similar to that of the original PE.

The alloying of polyethylene materials produces a material whose properties are dependent on the morphology of its constituents. Crystallinity was a key indicator in judging properties such as maximum elongation. Where small differences exist in the crystallinities of the constituents, calculating the properties of the resultant mixture was straightforward. When a number of very diverse polyethylenes are used, the final properties are much more dependent on the morphology of the blend.

More test data for the determination of the tensile properties would be useful in getting an accurate picture of the effects of heat cycling. As a number of the averaged data points showed a flat distribution further testing would help to improve the statistical accuracy of the test data. This was not done during the testing phase of this study due to time constraints.

Overall the data presented herein can be used to construct a series of models that will be able to predict the limits of performance of reclaimed polyethylene materials, based on a series of life-cycle factors. The results also show that waste polyethylene films with small amounts of contamination can be made into new products with a number of applications, depending on product specification.

# Chapter 7 – Liner and drainage systems

## 7.1 Introduction

This thesis has presented results to show that a sufficiently consistent product can be produced from recycled plastic film, and some of the effects of the recovery and recycling process have been outlined. Applications for these recycled film products should also be considered as part of the research as it is not feasible to recycle a waste product unless there is a suitably profitable market for the recyclate. In terms of feasible applications for the recycled film, this research also studied novel products. One product has a high-value application, arising from a fairly clean source. The other product has a low-value application using waste that is from a contaminated and therefore low-value source.

Two novel ideas for the application of recycled plastic products are shown in this chapter, the products developed are based in civil or landfill engineering applications and include geomembranes and porous drainage media. At present geomembranes are generally manufactured from virgin HDPE and international standards exist as to the specification of their physical properties when used for landfill engineering. Should a new product be developed for use in landfill geomembranes, it must satisfy these standards in order to be accepted, [83, 84].

For porous drainage media, current landfill technology generally employs aggregate stone as a barrier medium and to act as a large particle filter for the leachate (water that runs off a landfill) that is produced from the waste. The procurement of this material depends on the management of the landfill operation, although in the UK there are specifications in place by the Environment Agency as to the size and composition of this barrier [85].

Engineering barriers (such as geomembranes and filtration media) in landfill sites generally consume considerable quantities of virgin materials in their design and engineering construction. There is a general reluctance on behalf of the landfill regulators to use alternatives, despite the foreseen economic and environmental benefits. This reluctance comes from operators mistrust of using previously un-trialled products with no proven track record. To date, only limited research has been undertaken in this area, which would see recycled material being used within the engineering construction of landfills, rather than being tipped into them.

It is vital that the material chosen to operate as an engineering barrier does not degrade when in contact with landfill leachate, and the research shown herein investigates the effect of exposure to leachate on the physical properties of the replacement plastic materials. As leachate is a mixture of substances, which depends on the very nature of the landfill from which it originated, no standard exists to express its composition. In order to quantify its composition, leachate was sampled from a local landfill site and the geomembrane and filtration media were immersed in it for an extended period to determine whether their physical properties deteriorated after prolonged contact with the leachate.

## 7.2 Current standards

In assessing the engineering proposals for all landfill sites there are two basic rules that must be applied in all cases [85]:

- There must be no risk of unacceptable discharge/emission in the short, medium and long term.
- There must be structural/physical stability in the short, medium and long term.

Engineering barriers are the materials constructed within the base, sides and (after tipping is complete) top of the landfill to satisfy these rules. Engineering barriers within landfill systems are employed to contain and manage waste, landfill gas and leachate. By doing so, engineering barriers meet the fundamental requirement of both the Landfill Directive and the Groundwater Directive; that there is no risk of unacceptable discharge from the site over the whole lifetime of the landfill.

Engineering barrier systems within landfill operations, as shown in Figure 7.1, generally comprise of:

- Lining systems: To control seepage from landfill and landfill gas migration, retain consistent performance over site lifetime, and to control water ingress.
- Leachate drainage and collection systems: To prevent liquid levels rising and overflowing causing uncontrolled pollution, to reduce potential for seepage through lining materials, to minimise potential for chemical interaction between leachate and lining systems, and to encourage methanogenic decomposition of wastes. This is a potential area of application for the featured plastic drainage product.

- Capping systems: To contain waste, manage leachate production by reducing the ingress of water, control landfill gas, provide environmental protection for waste and to produce a visually acceptable landform.

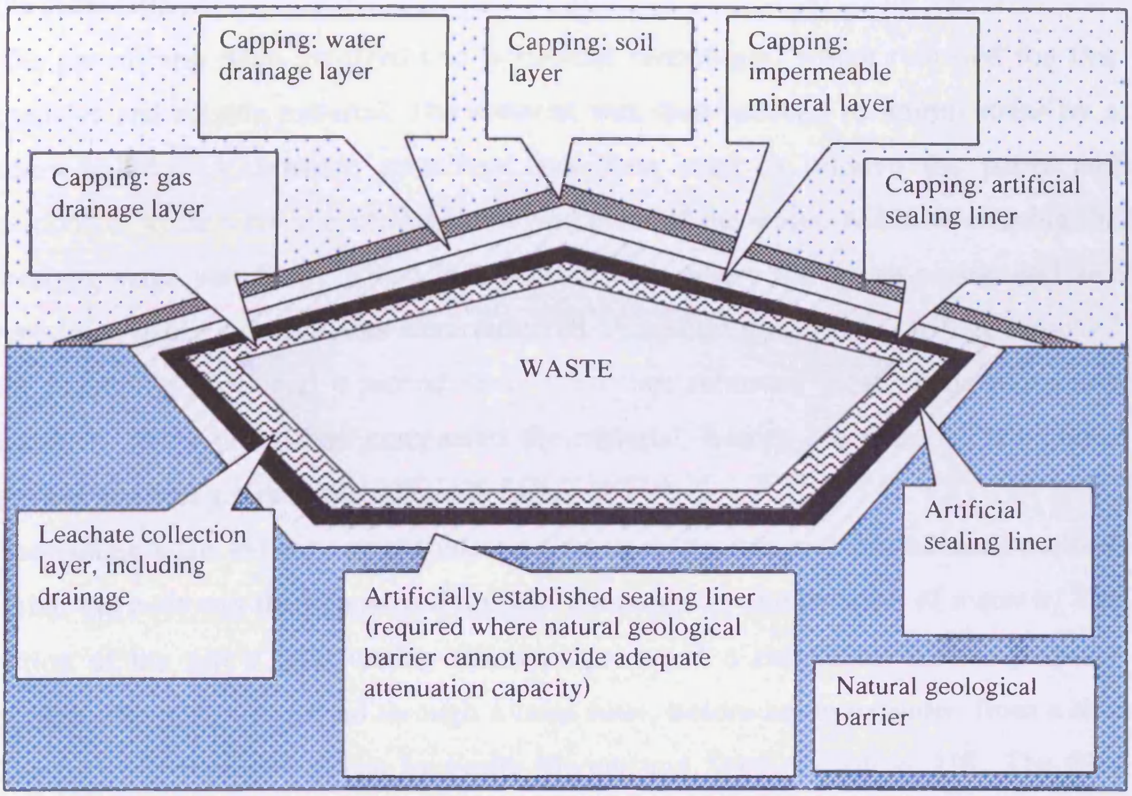


Figure 7.1 Engineering Barriers within Landfill Operations [85].

A geomembrane can be defined as a very low permeability synthetic membrane liner or barrier used with any geotechnical engineering related material so as to control fluid migration in a man-made project, structure, or system [84]. HDPE and LDPE are commonly used as landfill geomembranes, either as the main protective layer or in conjunction with other engineered barriers. The potential for recycled barriers therefore depends on the ability to meet the standards and performance of those liners in use today.

## 7.3 Origin of the materials developed, geomembrane material

As outlined in section 3.8.3, two tonnes of waste plastic film was collected and baled at a transfer station in North Wales, before being shipped to Southern Italy for processing at the ECOPLAST washing plant, using Tecnofer recycling technology. The film was hand sorted to remove major contaminants such as cardboard. The material was fed into a ripping/tearing shredder and reduced to strips of 100mm. The film was then fed into a stone trap where water and compressed air were used to carry the film across the trap while heavy contaminants sink and are removed. The recycling processes covered in this operation were outlined in a technical report on the plant [10].

The prewashing stage involved two horizontal centrifuges, which removed the fine particles and soluble material. The material was then reduced to 45mm strips by a screw grinder. A dynamic centrifuge was then used to remove the paper and cardboard, while a static centrifuge removed most of the water. Material entering the washing stage was firstly added to a settling tank where the dense plastic and any remaining dense contaminants were removed. A second dynamic centrifuge removed the remaining paper and a second static centrifuge removed most of the remaining water. A screw press then compacted the material, before the material fell into a grinder and was ground to less than 20 mm.

The pellets were fed into an extruder at Erema in Austria and heated until melting point; the melt was then conveyed through the barrel by the rotation of a screw. The action of the screw and heating elements produced a consistent molten polymer stream. The melt was forced through a laser filter, before being extruded from a die. The recycled film was blown by Frank Mercer and Sons of Bolton, UK. The film blowing equipment was used to a make a film product that resembled damp proof membrane at a thickness of 250µm. The 2.4mm thickness sheet material was made by Centriforce Products of Liverpool, UK.

## 7.4 Aggregate filtration material

The recycled pellets forming the basis of this investigation comprise a 50:50 part mix of "car-fluff" from Allied Steel and Wire Ltd, Cardiff, UK and Mixed Waste Plastics from a municipal recycling scheme in Germany. Several tonnes of this feedstock were sent to an agglomeration plant in Italy for mixing and pelletisation on a coarse scale.

"Car-fluff" is a term used for the material fraction that does not report to the magnetic separator after end-of-life vehicles have been fragmented. It is inherently heterogeneous, composition varies considerably between batches and is generally identified as being dirty unusable waste, normally sent to landfill. The "car-fluff" used in the present study was further processed by dense medium separation to remove the very dense particles. However, some non-plastic components, for example from electrical wiring looms, remained and visible fragments of metal such as copper and zinc were present. Further visual analysis showed that a small quantity of thermosetting plastic was also present.

It is fair to say that the waste from which this material has arisen from is a very-low value and high-contamination source, with a variable composition. It is possible that this material could be extracted from waste that failed quality control tests for material that might have been used for the geomembrane. This could potentially increase the efficiency of the production process for both materials.

## 7.5 Materials testing – experimental methodology

The membrane and drainage media were tested independently as they both have such different applications. Leachate was collected from a leachate sump at a municipal / commercial landfill site based in South Wales. The chemical composition of the leachate was assumed to be typical for the time of year, i.e. with the properties shown in Table 7.1.

Table 7.1 chemical composition of the leachate

| Property | Value |
|---|---|
| pH value | 6.2 |
| COD (Chemical Oxygen Demand) | 23800 mg/l |
| BOD (Biochemical Oxygen Demand) | 11900 mg/l |
| TOC (Total Organic Carbon) | 8000 mg/l |
| Fatty Acids (as Carbon) | 5688 mg/l |

### 7.5.1 Testing of geomembrane film material

For the Landfill geomembrane laboratory testing included the following standard tests:

1. Tensile Properties [83]. Used to evaluate the strength and elongation of the materials, and;
2. Puncture Resistance [84]. To evaluate the index puncture resistance of the materials.

These standard tests are of particular significance as they are basic indicators of the strength and durability of the materials, which are of primary importance in selecting a geomembrane material.

For the film material two sets of test specimens were prepared, to determine if the film was anisotropic. One was prepared with the major axis along the machine direction, distinguished by the process striations, and the other perpendicular to this axis. The standard tensile test principle involved extending a test specimen along its major axis (a uniaxial tensile force) at a constant speed of 500 mm/min, until failure of the specimen occurred. The load and the elongation of the specimen were recorded. Tensile and compression testing was undertaken using a tensile and compaction Testometric M500/50kN machine, a full methodology for this is given in Section 5.3 for the testing of injection moulded samples.

The puncture resistance test involved clamping a test specimen between circular plates. A steel rod was used to pierce the unsupported section of the sample until rupture occurred. The maximum force required to puncture the sample was recorded. In both cases for tensile and puncture resistance testing, the recycled material was compared with a geomembrane product currently employed at a modern landfill site.

### 7.5.2 Testing of aggregate filtration material

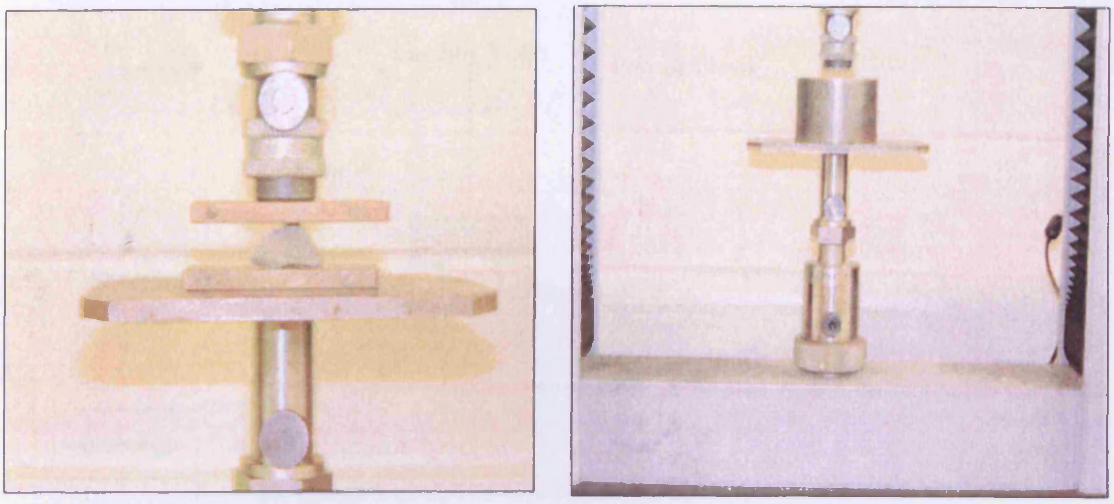
For the aggregate filtration material laboratory testing included the following standard tests:

1. Compressive testing from 0 to 50kN;
2. Shear box testing, based on BS 1377, and;
3. Permeability testing under increasing compressive load, up to a maximum of 50kN.

Ten single pellets and a combined mass of twenty mixed pellets, assembled in a metal cylinder, were compressed by the Testometric machine. Testing to determine the effects of leachate degradation involved repeating the compressive testing after each two-week period the plastic pellets were submersed in leachate.

Aggregate drainage stone and pellets previously unexposed to leachate were compressed in the same quantities. For single pellet testing, ten pellets were crushed individually. The compressing plate was driven downwards by the loading mechanism at a constant speed, and stopped automatically at the maximum load of 50kN. A photograph of this testing apparatus is shown in Figure 7.2.

Calculations based on measurements taken at a typical landfill site showed that the expected maximum pressure at the base of a landfill 40m in height is around 400 kN/m$^2$. The pellets were tested until they had been completely flattened to include the scenario of over-pressure, for example when a site compactor is driven over the waste.



(a) Compression of a single pellet

(b) Compression testing of 20 pellets in a cylinder

Figure 7.2 Compression testing of pellets.

To investigate the compressive behaviour of the mass of 20 pellets, rather than a single pellet on its own, a metal cylinder with a height of 4.5cm and an internal diameter of 4.4cm was used to contain them, as shown in Figure 7.2(b). Both pellets from the leachate tank and those previously unexposed to leachate were subjected to compression as a collective mass. Twenty aggregate drainage stones, with an approximate diameter of 15mm, similar in shape and size to that of the plastic pellets, were also subjected to a compression test, as a control. The cylinder was compressed to give an indication of how existing materials already employed at landfill sites behave as a mass under overburden pressure.

To evaluate the suitability of the pellets under a transverse (shear) load a shear box test was used. A schematic of this experiment if shown in Figure 7.3. The aim of the shear box test was to determine the shear strength of the recycled pellets, in order to assess their stability within and potential impact upon landfill engineering operations. Shear strength is a valuable property to understand as it determines the behaviour of the layer when acted on by a perpendicular force, as in the case of sloped banks.

Shear box testing was based on BS1377 [86]. The pellets were placed within the shear box to the dimensions of 60mm$^2$ and 20mm thick. The assembled box containing the pellets was placed in the container on the loading apparatus. A loading yoke was placed on top, and weights of varying size were added to give the required normal pressure, as shown in Figure 7.3. The box was then exposed to horizontal thrust to give a shear rate of 1.25mm per minute.

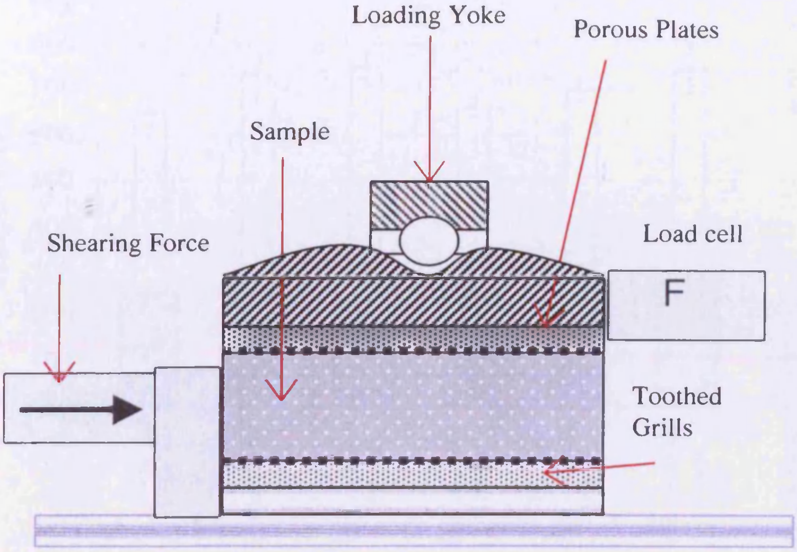


Figure 7.3 Shear box test apparatus

Permeability testing was performed to evaluate the materials ability to allow the passage of liquid. This was done using a drainage container, filled with the plastic pellets or aggregate stones. Water was drained through the pellets and was collected over a 30 second time interval. The dimensions and position of the drainage container were kept constant to ensure a constant head throughout the experiment.

After three runs of the permeability experiment (for data consistency) the cylinder and pellets were removed and compressed on the Testometric machine under forces increasing by 7kN each time. The compressed cylinder of pellets was repositioned back inside the drainage container after each phase of compression and the experiment repeated a further three times. This continued until a maximum load of 50kN was reached on the Testometric.

## 7.6 Results - landfill geomembrane

Figure 7.4 shows the results of the tensile testing for the 250μm thick recycled film, the 2.4mm thick recycled sheet material and the 1.5mm thick commercial capping material. The results for the film tested in the machine direction, and at 90° to the machine direction showed some variation. The variation was however within the standard deviation of each for the directions tested. Also shown on the figure are the properties of a capping material product, currently employed at the landfill site used for this investigation.

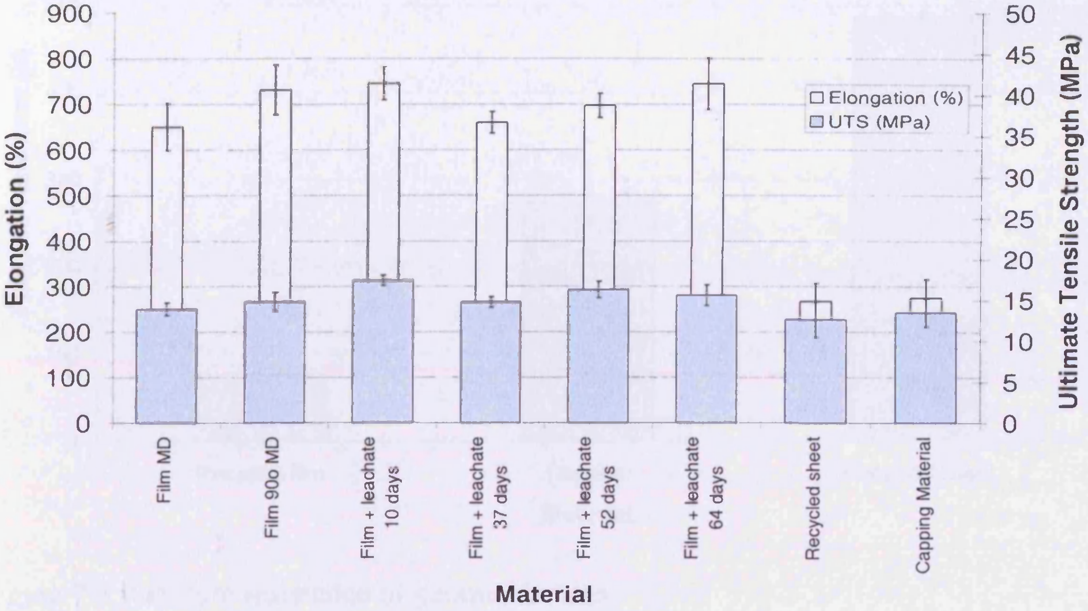


Figure 7.4 Ultimate tensile strength and maximum elongation of geomembrane materials.

The leachate chemical degradation tests showed that over the time period tested, there was no significant change in the tensile properties of the recycled film. The length of time the experiment was run was comparatively short, not long enough to provide definitive evidence that the tensile properties are not affected by the leachate over a period of years, but it has shown that no immediate effects were observed. Polyethylene as a material is chemically inert which is why the material is widely used as a landfill liner, therefore it is predicted that the tensile properties are unlikely to alter with prolonged exposure to leachate.

The maximum elongation for the film was significantly higher than for the capping material and the recycled sheet. This is a result of the film showing greater elastic behaviour as it can consistently ‘draw out’ during stretching, which is a known property of blown film. The UTS value of the film is similar to that of the capping material and the sheet. The capping material and the sheet show almost identical tensile properties in both UTS and maximum elongation.

Figure 7.5 shows the puncture resistance results. An increasing puncture resistance was observed with increasing thickness of the material. Consistency was evident in the data, with very low standard deviations between data points.

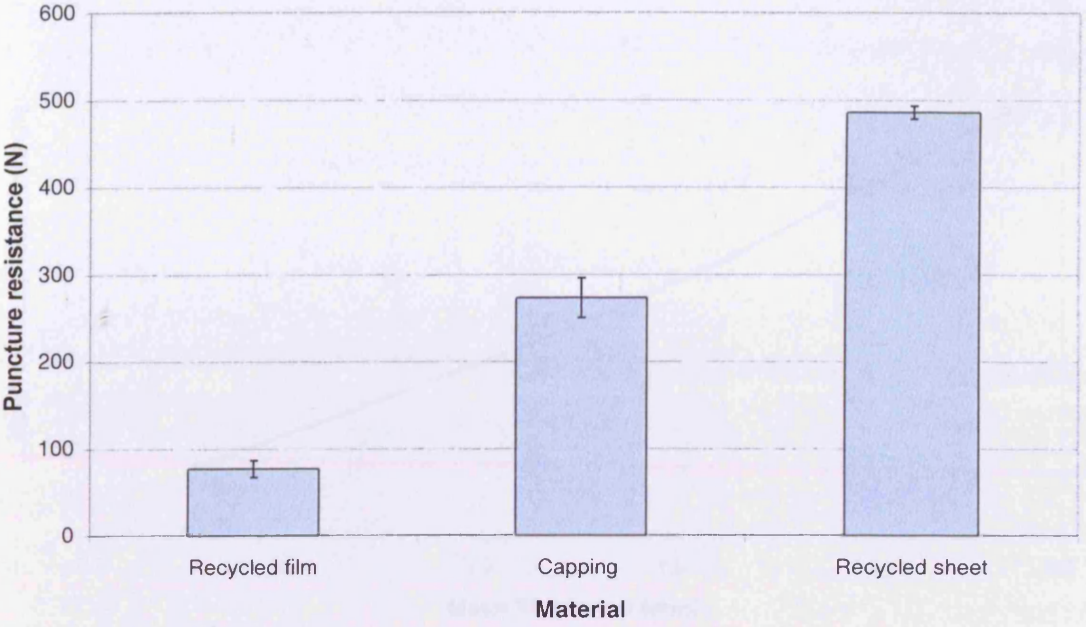


Figure 7.5 Puncture resistance of geomembranes

On first inspection, the data appears to show that the recycled sheet has a far higher puncture resistance that the capping material, which is in turn far more resistant than the recycled film. However, this is not a representative way of expressing the data, because each product had a different thickness.

Figure 7.6 shows a plot of mean thickness versus the puncture resistance, which illustrates the relationship between these factors. A linear trendline was fit to the relationship between film thickness and puncture resistance, illustrating that there is a straightforward relationship between thickness and puncture resistance for these materials. This was regardless of whether the material was recycled or from virgin stock, suggesting that the recycled sheet or film material would be adequate if it were made of thicker material.

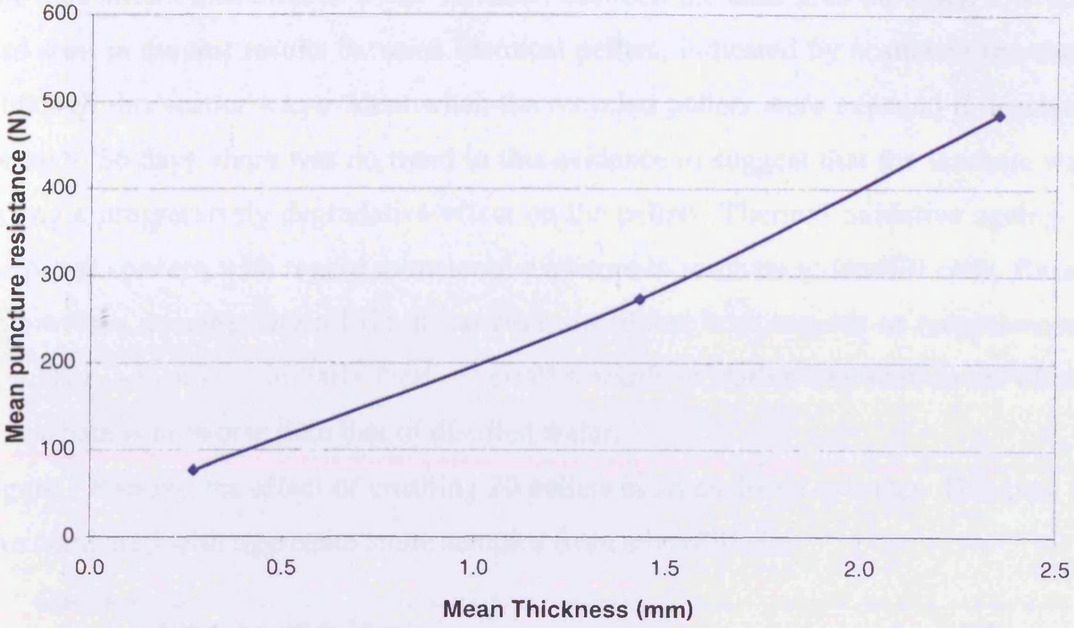


Figure 7.6 Puncture resistance expressed in terms of material thickness

## 7.7 Results - aggregate filtration material

Figure 7.7 shows the relationship between compressive behaviour and leachate exposure.

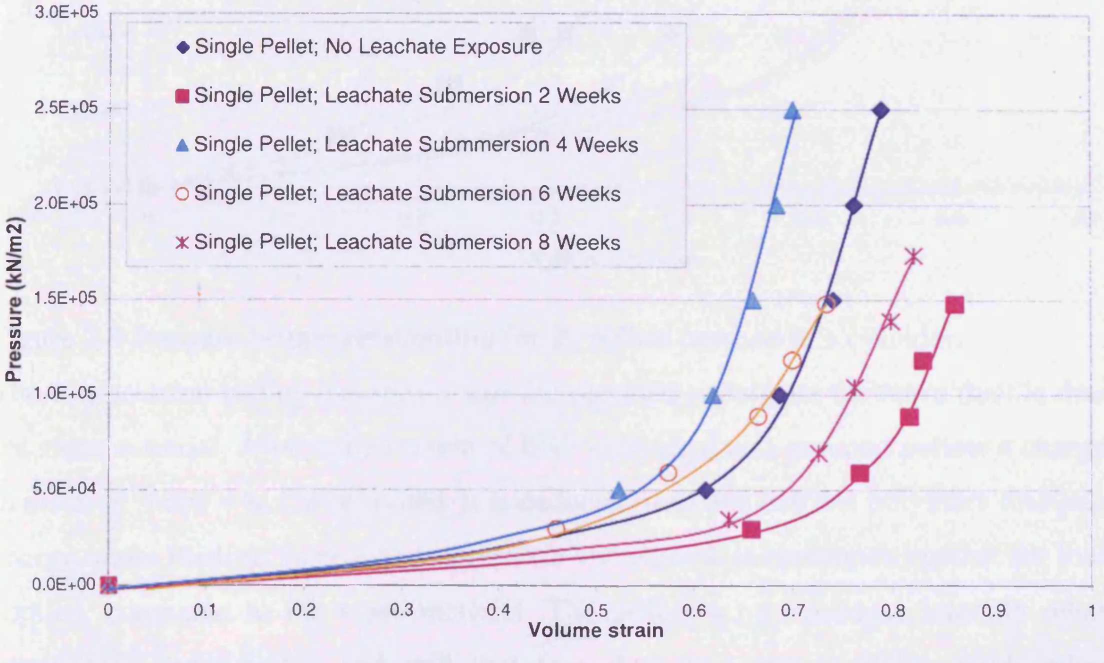


Figure 7.7 Pressure / strain relationship for single pellets in compression.

The data shows that there is some variation between the data sets, although this was also seen in the test results between identical pellets, indicated by scatter in the data. Although this scatter was evident when the recycled pellets were exposed to leachate for up to 56 days, there was no trend in this evidence to suggest that the leachate was having a progressively degradative effect on the pellets. Thermal oxidative ageing is the prime concern with regard to material exposure to leachate in landfill cells. Based on previous documentation [87], it has been noted that with regards to receptiveness of rubber (which is a similarly inert material) towards oxidative degradation the effect of leachate is no worse than that of distilled water.

Figure 7.8 shows the effect of crushing 20 pellets in an enclosed cylinder. This data is also compared with aggregate stone samples from a landfill site.

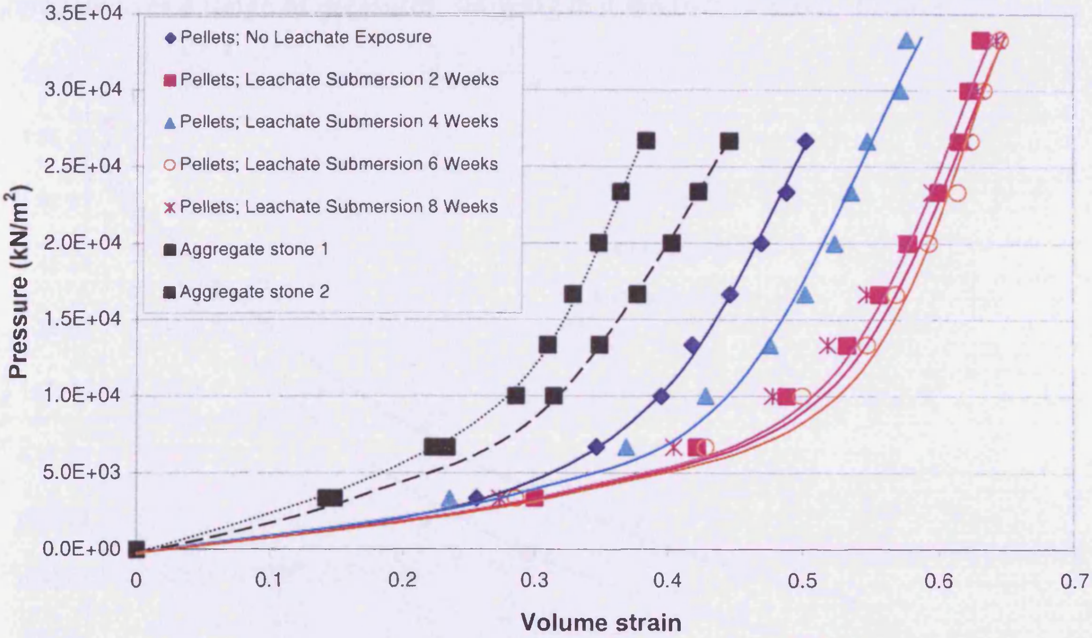


Figure 7.8 Pressure / strain relationship for 20 pellets crushed in a cylinder.

The compression testing has shown that the recycled pellets are far more ductile than the stone material. After compression of both individual and grouped pellets a change in material shape was always noted. It is deduced from this that the polymers dissipate energy under loading; they are compressible and show less resistance against the load applied, compared to the stone material. The pellets act to collapse laterally when compressed individually, and will therefore flow into any available voids when compressed as a mass.

It is advised however that creep testing under compression and shear should be undertaken to substantiate this comparison [88]. It should also be taken into consideration that the leachate used in this testing is of non-hazardous landfill origin, and if the pellets were to be used as drainage layers in hazardous sites, further testing with leachate obtained from such sites would be required.

Compressive behaviour of stone drainage aggregate is entirely different. Stone aggregates are brittle therefore there is no shape change under compression and the material appears to be crushed rather than gradually deformed by increasing loads. The difference in pellet and aggregate behaviour under loading is demonstrated in Figure 7.8. An increase in load leads to an increase in deflection. The data shows that the recycled pellets generally exhibit larger deflections than the aggregate at equivalent loads.

Figure 7.9 shows the hydraulic conductivity of the recycled pellets and stone aggregate over a range of pressures, showing that the two materials behave similarly.

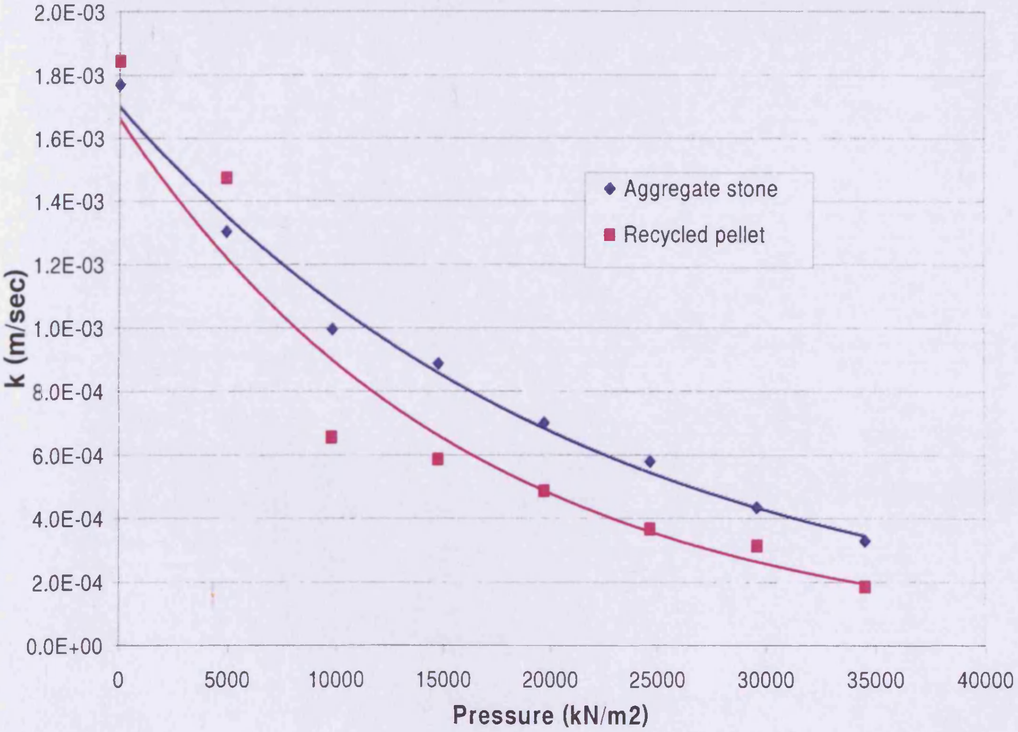


Figure 7.9 Permeability of drainage materials over a range of applied pressures.

At zero applied pressure the permeability of the two materials is almost equal. Above a pressure of around 5000 kN/m$^2$ the permeability of the recycled pellets become less than that of the stone aggregate and this trend continues for the rest of the pressures that the materials were exposed to in this experiment. Above a pressure of around 10000 kN/m$^2$ the permeability of both materials decreases steadily, with the difference between them remaining approximately constant.

It can be concluded therefore that aggregate drainage stone marginally provides a higher hydraulic conductivity when emplaced in the base of landfill cells. However, given that stone aggregate drainage layers are the most dominantly used in UK landfill sites, and the co-efficient of permeability values deduced in this investigation are very similar for both materials, it seems feasible that the recycled pellets will have adequate permeability for landfill drainage layer emplacement.

Figure 7.10 shows the results of the shear testing of the recycled pellets. Also shown on the graph are the shear / nominal stress relationships for typical sand and gravel materials.

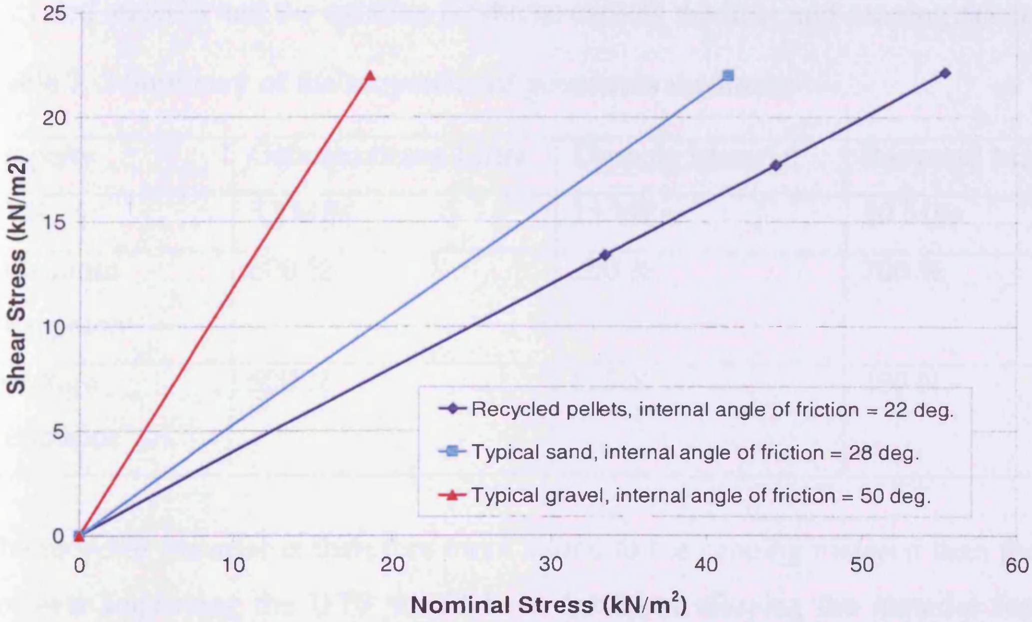


Figure 7.10 Relationship between nominal and shear stress for recycled pellets.

The pellets have an angle of internal friction of 22°, which can be compared to values for sand and gravel that are in the range of 28° to 50°, as highlighted in Figure 7.10. Being cohesionless (pellets have no resistance due to lack of forces holding them together in a solid mass); the calculated internal angle of friction of the pellets will have to be taken into account if they are to be employed as drainage material. It is subsequently deduced that the pellets will not significantly affect the stability of a landfill if employed directly on the base of the cell, but further calculations are necessary (based on proposed cell dimensions) if they are to be emplaced on perimeter side slopes.

## 7.8 Summary

Two products made from recycled plastic for use in modern landfill engineering have been presented. In both cases the products could be used to replace existing landfill barriers, although consultation would be necessary to ensure that the particular landfill in question was within the parameters covered by the tests in this investigation. The standards that exist to specify the mechanical properties of these products have been met by the testing covered in this study [84, 83, 85, 86]. Pilot testing would be required to demonstrate that the products are feasible for an industrial application.

For the geomembrane liner, Table 7. 2 shows a summary of the data collected on the recycled material and the existing products, namely the liner and capping material.

Table 7. 2 Summary of the properties of geomembrane liners

| Property | Geomembrane Liner | Capping Material | Recycled Material |
|---|---|---|---|
| UTS | 53 MPa | 15 MPa | 20 MPa |
| Maximum Elongation | 600 % | 250 % | 700 % |
| Puncture Resistance | 500 N | 175 N | 480 N |

The recycled material is therefore more suited to the capping material than the liner, however improving the UTS would be a matter of alloying the material feedstock with a higher UTS material such as HDPE. At 700% maximum elongation the material could be strengthened without compromising or failing the ductility standard required for the material.

Design specifications for liner systems universally specify that the material must only contain virgin polyethylene resins. The potential contaminants in the recycled product would have to be investigated. Any substitute for a geomembrane would have to be of an equal specification. Therefore to further the investigation the analysis should be extended to cover all the ASTM and BSI standard tests commonly used.

For the drainage media, Table 7.3 shows that the properties of the plastic material are similar to the stone material and could be used for landfill applications after further pilot testing.

Table 7.3 Summary of the properties of landfill drainage media.

| Property | Stone Aggregate | Recycled Material |
|---|---|---|
| Compressive Testing | Vol strain about 0.35 | Vol strain about 0.5 |
| Permeability | $1.5 \times 10^{-3}$ m/sec @ 5 MPa | $1.3 \times 10^{-3}$ m/sec @ 5 MPa |
| Shear Testing | Angle of friction 50° | Angle of friction 22° |

The biggest difference between the two materials was found in shear testing, implying that the plastic may not be as suited to sloped environments, but as a base material on a flat site it would be acceptable.

# Chapter 8 – Life-cycle factor modelling

## 8.1 Introduction

The determination of degradative factors on polyethylene materials and application to an engineering product have been illustrated in Chapters 6 and 7 respectively. The next stage in the development process of this study involved applying physical data for modelling. This original piece of work is concerned with utilising the data presented in Chapter 6 in order to forecast an operational envelope in terms of the condition of the input (waste) material to a recycling facility.

The thesis has already covered film recycling processes and the impact of life-cycle conditions (i.e. degradation factors such as heat cycling, tape addition and dirt contamination) on the mechanical properties of the film. To apply the experimental data in a practical fashion, it would be desirable to define the acceptance limits of factors such as contamination, process cycling and polymer mixture ratios. Such limits would then identify the potential boundaries to which plastic film recyclers could work within and base acceptance criteria for input material to recycling operations.

This novel technique has not been developed in previous industrial practice or research. Current techniques for assessing the quality of recyclate feedstock have never attempted to forecast the physical properties of the material prior to reprocessing. Normally a material would either have a specification because it was from a clean and identified industrial source (e.g. an unused batch), or it would be treated as "mixed plastic waste" and used to make low-value products of limited specification [2, 3]. This life-cycle factor modelling technique is unique because it gives a reasonable estimation of the physical property envelope without the need to fully recycle the material beforehand. This was made possible by employing the unique information gleaned from the life-cycle factor data in the experimental portion of this investigation.

The purpose of developing such a model was that it can be used as a tool for the decision making process by recyclers when accepting material. Two of the biggest factors to blame for problems when recycling plastic are:

1) The inability to realistically estimate the effect of contamination, which is why many recyclers are reluctant to work with unfamiliar material. As stated

previously recyclers are more likely to only accept material from a clean and reliably consistent source, usually when the material has been hardly used [2, 89].

2) The lack of trained staff to decide whether the input material was suitable for the application in question. Assessment of the condition of plastic waste is normally undertaken by experienced engineers or polymer experts. For this reason factory-floor staff do not have the expertise or authority to assess the condition of a feedstock batch. Such assessment by specially trained workers proves to be financially unfeasible [76].

These issues can be addressed by developing a model that will quantify the state of a material feed in order that advice could be sought on whether to accept the material. Criteria for acceptance will be based on a number of mechanical properties that the material must meet and will depend on the recycled products under consideration, although from a manufacturers point of view, processing properties such as MFI will be of primary concern. No techniques are currently in existence to quantify the state of recycling feedstocks, so this novel approach would be more effective than guesswork.

Waste material arriving at a recycling operation will not contain a specification of material properties, nor will it be straightforward to estimate how the life-cycle factors will affect the resultant product. Therefore a predictive model will be useful as it could suggest to the recycler the resultant properties of the feedstock, which could then be used to determine the suitability for recycling at the plant in question. Should the material not be within acceptance criteria it could be sold to reprocessors that stipulate lower specifications for feedstock material.

## 8.2 Model outline

A numerical model was prepared to combine the effects of life-cycle factors into a number of quantitative results. These results would then be used to:

1) Estimate the mechanical properties of a product manufactured using the input material and its life-cycle.
2) Suggest whether the final product would be suitable for the application and what, if any, changes could be made to the input to make it meet the required standard, i.e. cleaning or further sorting to remove a contaminant. Critical

material properties, such as MFI would be examined to determine whether the recycled material would be suited to the manufacturing process in question.

Literature searches to determine whether this subject had been addressed previously found that there were no instances of modelling schemes to predict the effect of life-cycle factors on plastic material. In terms of material specifications only one guide was found to be in existence, known as PAS 103, as introduced previously [90]. This specification acts to determine the types of plastic and types of contamination that can be found within them, it does not go further to suggest the effect of or how much of any life-cycle factor is acceptable. In a practical scenario, recyclers would be interested in the quantity and consequence of life-cycle factors, not just in determining a classification for them.

This lack of quantitative schemes to assess life-cycle changes highlights the fact that plastic recyclers choose their own acceptance criteria based on the relationship with the suppliers of the waste product. Generally speaking, acceptance of a batch of film is based on the appearance of the feedstock and from periodic testing of small batches after the recycling process. Should a sample fail the quality control test, it is likely that the batch from which it originated will be recalled.

Data based on material testing showed that the basis of the model should focus on the crystallinity of the polymers present in the input to the recycling plant. Crystallinity is the most reliable property for which to base modelling calculations because it is the property that governs the overall physical properties of a polymer (such as MFI) and can indicate changes in material properties most accurately. Figure 8. 1 shows a schematic of the application of the model. The development of the calculations on which this model was based is shown in the next section.

The application of the model at a theoretical recycling plant involves the steps shown in Figure 8. 1. The operation generally comprises of:

- Plastic film feedstock is delivered to the plant and prepared for inspection. A small representative sample of the plastics only is extracted.
- The plastic waste to be recycled is evaluated for material properties using simple and inexpensive apparatus.
- The material's crystallinity is calculated based on correlations with the above measured physical properties.
- The life-cycle factors are inspected, measured and recorded.

- The crystallinity is then re-calculated based on the effect of life-cycle factors, such as number of heat cycles, amount of tape in the mixture or alloying effects, as derived in Chapter 6.
- The resultant crystallinity is then used to back-calculate resultant physical properties such as MFI, UTS and maximum elongation.
- With these new values the recycler can decide whether the material batch at the plant would produce a product that meets its specifications or if the material should be rejected. This would save money as the expense of having to recycle the batch can be avoided if the material were to fail specifications.

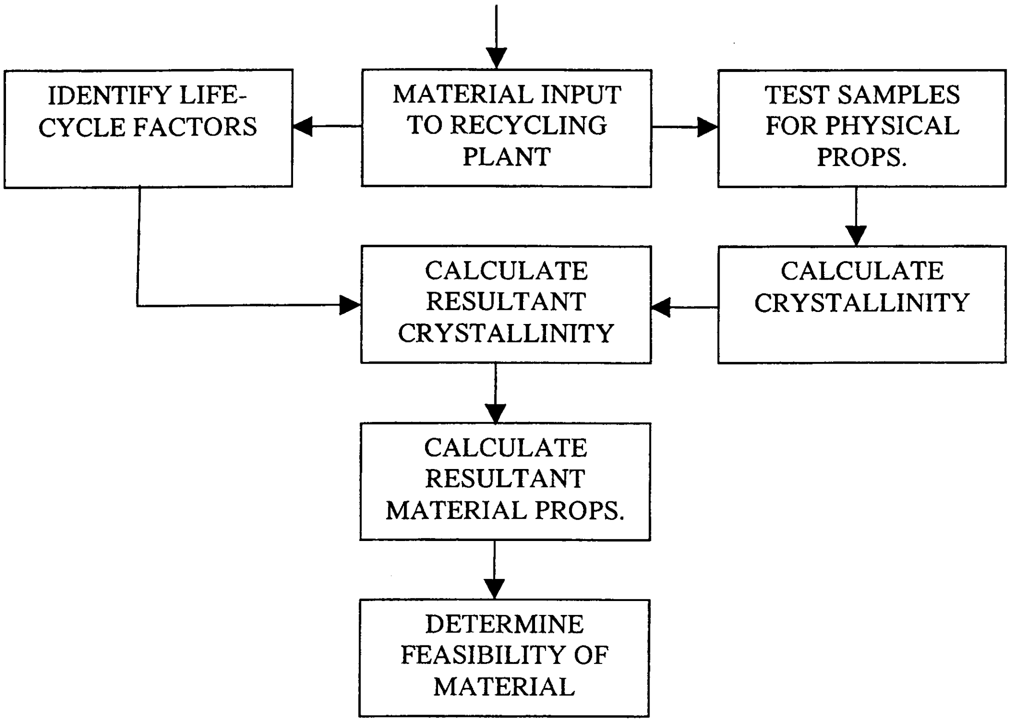


Figure 8. 1 Overall schematic of the predictive model showing main steps to find the effects of life cycle factors on recyclate feedstock.

## 8.3 Development methodology

The model was developed in four stages.

1. **Matching of correlations in data for physical properties.**

The relationships between physical properties were then examined. This involved finding the relationship between these properties for a number of polymers, for example between UTS and PI. Correlation coefficients were then used to determine which physical property had the strongest correlation with the others and could therefore be used to base the model calculations.

2. **Analysis of experimental data on life-cycle factors.**

   Data from Chapter 6 was used to determine the relationship between the magnitude of life-cycle factors and the change in physical properties, e.g. the change in UTS with increasing amounts of PP tape.

3. **Assemblage of numerical model.**

   The model was programmed with the above correlations and run to calculate resultant values of material properties given the life-cycle factors to which the material had been exposed.

4. **Evaluation of accuracy**

   Finally the overall accuracy of the model was investigated to see if the calculation stages had introduced significant errors into the results. This was achieved by comparing the calculated results to experimental results measured previously. Previous data was available from the physical results presented in Chapter 6 and used as a comparison validate the model.

To determine the correlation between physical properties, previously measured experimental results were examined to determine if any relationships were present that may be used to predict changes in material properties based on potential material life-cycles. The properties used for this were:

- Ultimate tensile stress (UTS).
- Maximum Elongation.
- Melt flow index (MFI).
- Crystallinity.
- Molecular weight (Mw).
- Polydispersity index (PI).

After considering all the possible correlations between the properties listed above it was found that crystallinity was the most reliable property, as it had the most consistent relationship with the five other properties, i.e. the least amount of scatter in correlation based on experimental data. It was also found that changes due to life-cycle factors, such as heat cycling or alloying gave the most consistent relationships with crystallinity than the other properties, which is discussed in the results section of this chapter. After further investigation it was determined that crystallinity could be reliably estimated to an accuracy within ±10% of the actual measured value. This was when the crystallinity was calculated based on an average between the values found using the experimentally determined correlations.

The next step in building the model involved using the derived relationships between life-cycle factors and the change in crystallinity, as outlined in Chapter 4 and measured experimentally in Chapter 6. These factors are listed below:

- Successive heat cycles.
- Dirt contamination.
- Adhesive tape contamination.
- Mixing (alloying) with other polyethylenes.

It was found that the factors could be effectively used to estimate a new value of crystallinity, based on the condition of the material. This was carried out by comparing calculated values to experimentally measured values (for example finding the effect of adding 5% talcum to virgin LDPE both experimentally and by estimation using the model). Calculating the effect of mixing (alloying) was done by averaging the crystallinity of the different fractions present in the mixture. A schematic representation of the whole process is given in Figure 8.2.

As the figure shows, the resultant crystallinity was calculated based on the crystallinity of the materials present in the mixture, after the effect of their life-cycles has been found. In the case of Figure 8.2 only two mixtures are shown, but the model was programmed to calculate the resultant crystallinity based on any number of material feeds.

The final step in developing the model was to determine its overall accuracy by finding whether the resultant mechanical properties (i.e. UTS, maximum elongation and MFI) of the polyethylenes could be back-calculated reliably using the inverse of the relationships that had been derived from experimental data. This was undertaken to find an approximate value of the accuracy of the model. Existing data expressing the effect of contamination and heat cycling scenarios had been experimentally measured from work covered in Chapter 6. These experimental values were compared to calculated values from the output of the model.

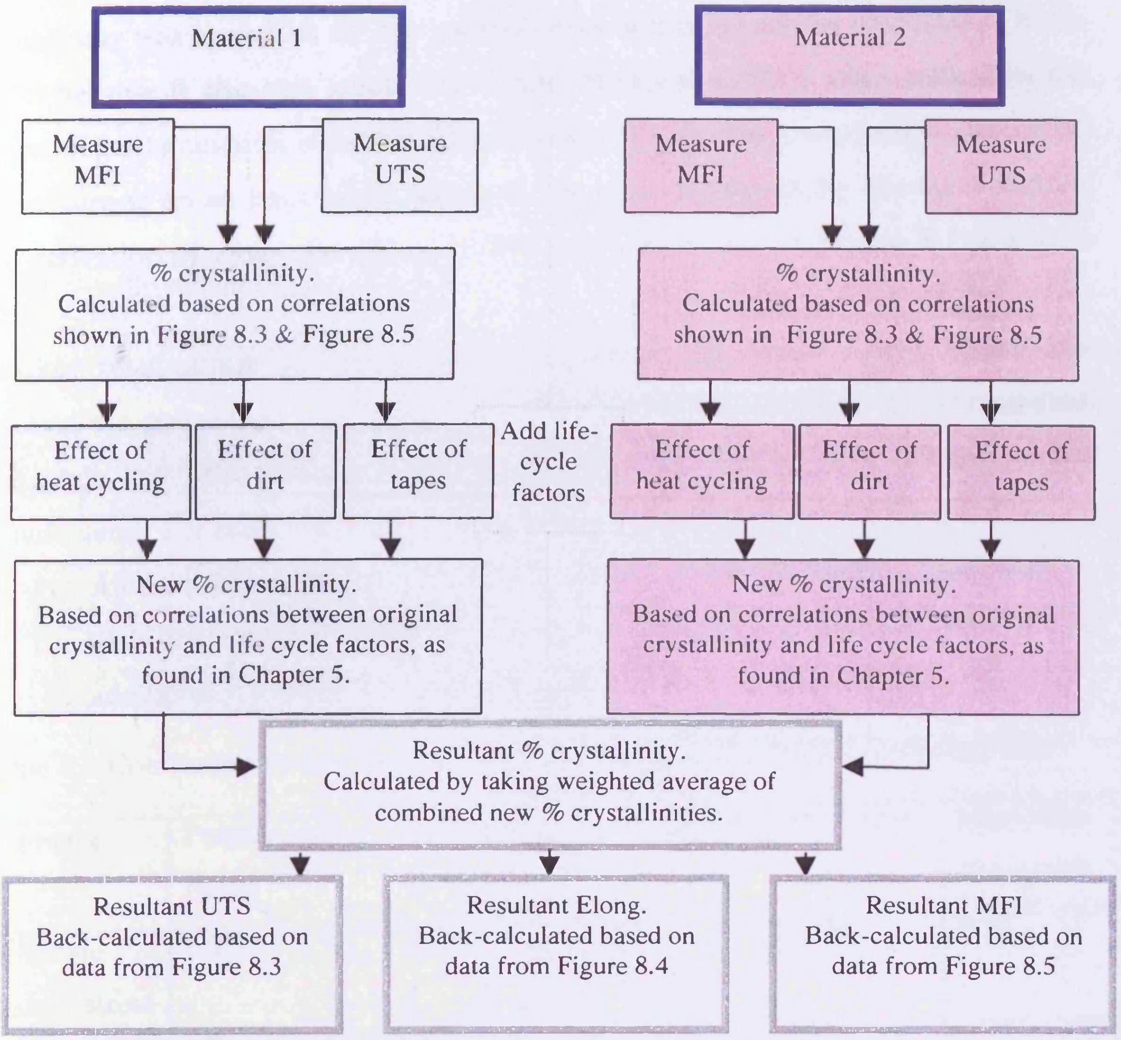


Figure 8.2 Schematic showing the calculation process and main steps for a mixture of two plastic materials.

## 8.4 Results and accuracy of the material property correlations

### 8.4.1 Introduction

Having introduced the steps taken to determine the operation of the model, the data used to produce the correlations and trends will be presented. Also shown will be the actual calculation steps that determine the crystallinities of the polymers.

### 8.4.2 Correlations and their accuracy

Table 8.1 shows a matrix of correlation coefficients ($R^2$), as determined by a spreadsheet package, for the six measured properties [91]. The correlation coefficient is a quantity that gives the quality of a least squares fitting to the original data. This data was found using the existing results from Chapter 6. The properties with the highest correlation factors (i.e. the least amount of scatter when compared to the others) are UTS and crystallinity.

Crystallinity was chosen as the key parameter for which to base the calculations in the model because it also was found to be more reliable than UTS when estimating the effects of contamination after further evaluation. It was also more indicative of what was occurring on an intra-polymeric level due to the action of the life-cycle factors. The derivation of these correlation coefficients can be seen in Figure 8.3 to Figure 8.5.

The key relationships of interest to this aspect of the work are the interactions between the percentage crystallinity and the material properties of UTS, maximum elongation and MFI (because these three parameters are of most interest in film manufacture). For each result two series of data are presented in the figures below:

1. All the data points collected during the test results presented in Chapter 6.
2. Only the "ground values" i.e. material in its uncontaminated state with no additional life-cycle factors, such as heat cycling or tape addition.

Table 8.1 Coefficient values for correlations between measured physical properties.

| **Versus** | Polydispersity Index | Molecular weight | Crystallinity | Melt flow index | Maximum elongation |
|---|---|---|---|---|---|
| Ultimate tensile stress | 0.75 | 0.89 | 0.89 | 0.76 | 0.89 |
| Maximum elongation | 0.39 | 0.59 | 0.8 | 0.69 | |
| Melt flow index | 0.76 | 0.76 | 0.85 | | |
| Crystallinity | 0.6 | 0.83 | | | |
| Molecular weight | 0.8 | | | | |

Ground values refer to the measured physical properties of the polymers with no additional life-cycle factors added. For example this would mean a pure polymer sample that has not undergone any additional heat processing cycles, been exposed to non-plastic contaminants or been alloyed with other polymers. A ground value's XRD measured crystallinity will be solely based on the morphology of the polymer chains, rather than the heat processing effects or contaminants contained within the material.

Therefore it is logical to base modelling calculations on material ground states because the reference is pure polymer, rather than some adjusted value caused by the factors themselves. The modified crystallinity will take account of the life-cycle factors imposed on the pure (ground state) material, so it is more accurate to base the correlations on pure material only.

Figure 8.3 shows the relationship between crystallinity and UTS for all the materials tested, as well as the ground values for uncontaminated material. The trends are both linear, with the ground values showing less scatter.

The graph suggests that scatter is more likely from the data where some form of life-cycle test was performed, i.e. altering the material in some way such as cycling or the addition of contamination. There was a stronger correlation between crystallinity and UTS when ground values were used, this was found to be 89%.

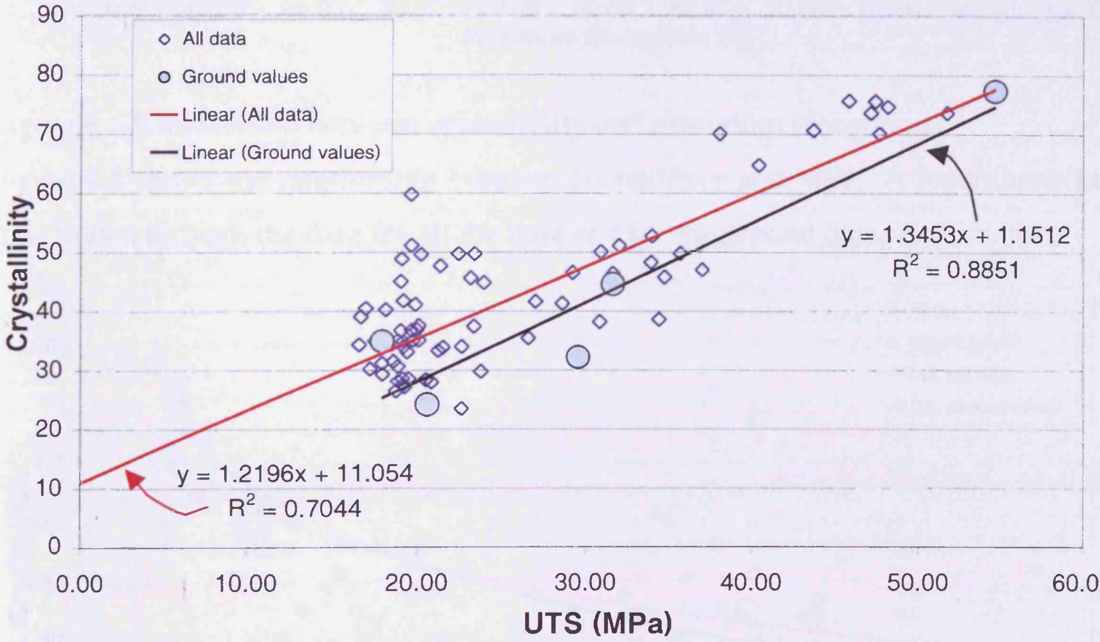


Figure 8.3 Relationship between crystallinity and ultimate tensile strength

Figure 8.4 shows the relationship between crystallinity and maximum elongation. The correlation between the two was far weaker that the case with UTS. There was also a diversion in the results where some contamination tests suggest the relationship was linear, but the ground values appear to have a power relationship.

As the correlations appear to be weaker in the case of maximum elongation, it was decided that calculations of crystallinity should not be based on this property. This factor also explains the lower degree of accuracy when calculating resultant elongation as explained later.

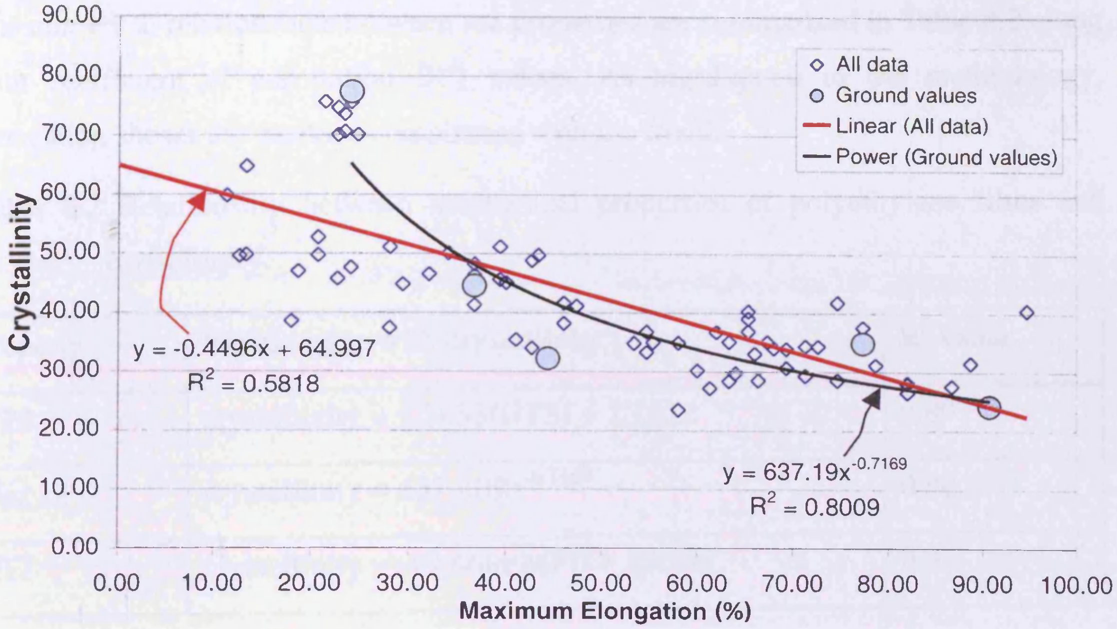


Figure 8.4 Relationship between crystallinity and maximum elongation

Figure 8.5 shows the relationship between crystallinity and MFI. A logarithmic best fit is drawn through the data for all the data and for the ground data.

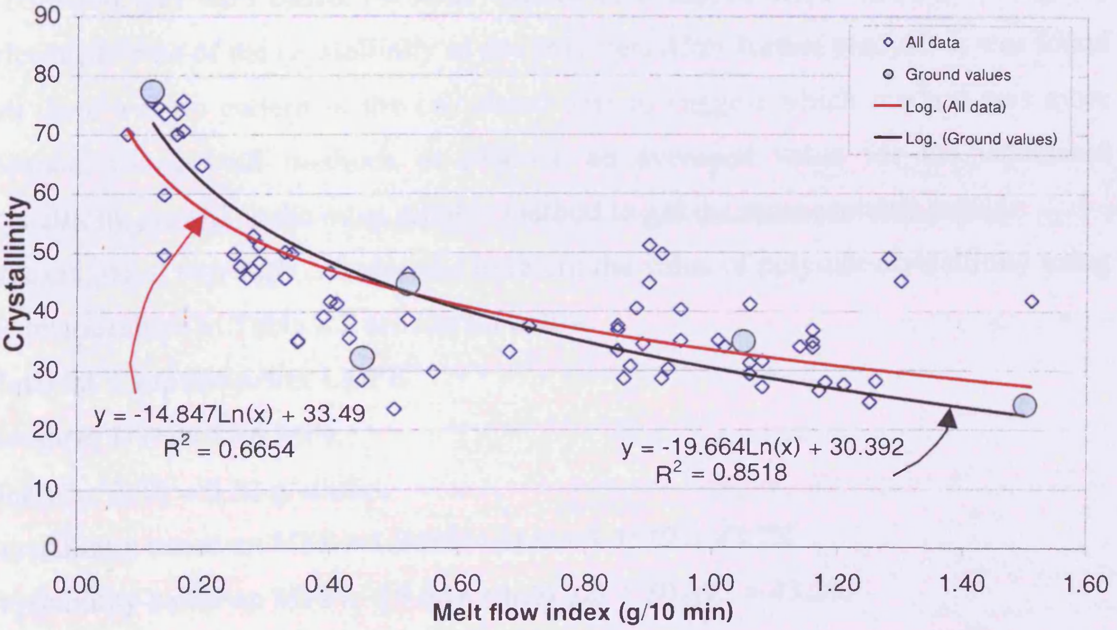


Figure 8.5 Relationship between crystallinity and melt flow index

The graph shows that the results are similar to UTS inasmuch as there was a fairly strong (around 85%) correlation between the two properties, based on ground values.

The data in Figure 8.5 fits with greater accuracy to a logarithmic curve for both the whole data and the ground values.

The numerical relationships between the properties are summarised in Table 8.2 along with coefficient of correlation ($R^2$) values. As highlighted in the methodology, elongation shows the weakest compliance with the trend.

Table 8.2 Relationship between mechanical properties of polyethylene films and crystallinity.

| Property | Relationship with crystallinity | $R^2$ value |
|---|---|---|
| UTS | crystallinity = 1.3453(UTS) + 1.1512 | 0.89 |
| Max El | crystallinity = $637.2(\mathrm{El})^{-0.7169}$ | 0.80 |
| MFI | crystallinity = -19.66ln(MFI) + 30.392 | 0.85 |

## 8.5 Operation of the model and worked examples

The model operating procedure is shown in this section. The calculation steps are the same as in Figure 8.2. When calculating the crystallinity it was found that both the UTS-based and MFI-based methods experienced inaccuracies when returning the calculated value of the crystallinity of the polymer. After further analysis it was found that there was no pattern in the calculated data to suggest which method was more accurate. Using both methods to produce an averaged value for the calculated crystallinity proved as the most reliable method to get the most accurate result.

An example of two such calculations to return the value of polymer crystallinity using the relationships in Table 8.2 are shown below.

**Material = supermarket LDPE**

Measured UTS = 31.6 MPa.

Measured MFI = 0.52 g/10min.

Crystallinity based on UTS = 1.3453 × 31.6 + 1.1512 = 43.7%

Crystallinity based on MFI = -19.664 × ln(0.52) + 30.392 = 43.3%

Average crystallinity = 43.5%

Measured crystallinity using XRD = 44.6%

In this case the UTS method was more accurate, but this is not always the case as shown below.

**Material = virgin LDPE**

Measured UTS = 20.6 MPa.

Measured MFI = 1.5 g/10min.

Crystallinity based on UTS = 1.3453 × 20.6 + 1.1512 = 28.9%

Crystallinity based on MFI = -19.664 × ln(1.5) + 30.392 = 22.4%

Average crystallinity = 25.6%

Measured crystallinity using XRD = 24.2%

In this case the MFI method was marginally more accurate. This highlights the fact that using two independent methods to calculate the crystallinity and averaging the result makes the procedure more reliable, since no particular method was consistently more reliable.

With the crystallinity value of the pure polymer calculated, the model would then adjust the crystallinity based on the life cycle factors. An example is given below:

**Material = virgin LDPE, 3 heat process cycles, 5% dirt contamination**

Calculated average crystallinity = 25.6% (from previous calculation). Adjustment due to heat process cycling was based on the relationship between the crystallinity of LDPE and heat processing cycles as shown in Figure 6.10. The relationship was approximated with a linear fit of an increase in crystallinity of 3.6% per heat cycle. Thus, adjustment factor due to heat process cycling = 3 × 3.6 = 10.8% change.

Adjustment due to dirt contamination was based on the relationship between the crystallinity of LDPE and talc contamination as shown in Figure 6.22. The relationship was approximated with a linear fit of an increase in crystallinity of 5% per 1% of talcum contamination.

Thus, adjustment factor due to dirt (talcum) contamination = 5 × 5 = 25.0% change.

So, new mixture crystallinity = 25.6 ×(1+(10.8 + 25.0)/100) = 34.8%

The effect of the life-cycle factors was best expressed by a linear approximation, i.e. percent change in crystallinity caused by percent increase in life-cycle factor, as shown in the previous calculation. The use of linear relationships was undertaken for two reasons:

- To keep the operation of the model simple.
- To show general overall trends, because the crystallinity change was often different for different materials.

The matrix used to calculate the changes in crystallinity from all the studied life-cycle factors is shown in Appendix I.

With the change in crystallinity calculated, the model calculated the effect of alloying. If there was more than one polymer in the mixture (for example an LDPE and HDPE mixture) the model took a weighted average of the resultant crystallinities of the constituents. Life-cycle factors were applied before this averaging step because the change in crystallinity of the polymer can depend on its molecular weight for factors such as heat processing cycles. An example of this calculation is given below:

**Material = 25 % virgin LDPE plus 75% HDPE carrier bag material**

Calculated crystallinity of virgin LDPE = 25.6 %

Calculated crystallinity of HDPE = 73.6 %

Resultant crystallinity = (0.25×25.6)+(0.75×73.6) = 61.6

In the final step of the procedure, the model would then back-calculate the values of UTS, elongation and MFI from the new crystallinity (values in bold). This was achieved by taking the inverse of the relationships given in Table 8.2:

**Material = virgin LDPE, 3 heat process cycles, 5% dirt contamination**

Calculated crystallinity = **34.8%**

UTS = $(\mathbf{34.8} - 1.152) / 1.3453$ = 25.0 MPa

El% = $2942.3 \times (\mathbf{34.8})^{1.1171}$ = 55.8%

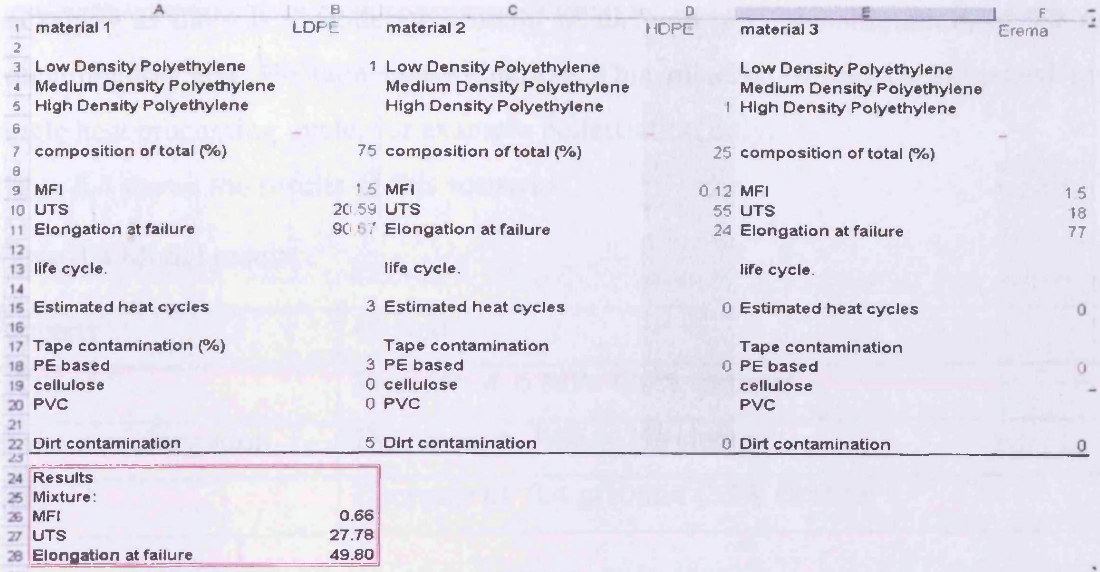
MFI = $-e^{(\mathbf{34.8} - 30.392)}/19.664$ = 0.8 g/10min

These new values are the final outputs of the model on the front user spreadsheet, as shown in Figure 8.6.

## 8.6 Typical outputs and example recycling scenarios

The model was used to calculate the resultant properties of a series of input scenarios. A picture of the input spreadsheet of the model is given in Figure 8.6. Material varieties are listed across the top, with life-cycle factors and associated data running vertically across the spreadsheet. Resultant values of MFI, UTS and elongation are listed in a separate space for clarity.

Three example scenarios are given below that express possible input feeds to a recycling plant. The model was used to find the change in material properties when some example types of PE with different heat cycles and contamination levels were recycled. The results are given as a change in material property, along with a percentage change, based on the original value of that property. The results are commented on in terms of expected values and the significance of the new materials' recyclability.



| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | material 1 | LDPE | material 2 | HDPE | material 3 | Erema |
| 2 | | | | | | |
| 3 | Low Density Polyethylene | 1 | Low Density Polyethylene | | Low Density Polyethylene | |
| 4 | Medium Density Polyethylene | | Medium Density Polyethylene | | Medium Density Polyethylene | |
| 5 | High Density Polyethylene | | High Density Polyethylene | 1 | High Density Polyethylene | |
| 6 | | | | | | |
| 7 | composition of total (%) | 75 | composition of total (%) | 25 | composition of total (%) | |
| 8 | | | | | | |
| 9 | MFI | 1.5 | MFI | 0.12 | MFI | 1.5 |
| 10 | UTS | 20.59 | UTS | 55 | UTS | 18 |
| 11 | Elongation at failure | 90.67 | Elongation at failure | 24 | Elongation at failure | 77 |
| 12 | | | | | | |
| 13 | life cycle. | | life cycle. | | life cycle. | |
| 14 | | | | | | |
| 15 | Estimated heat cycles | 3 | Estimated heat cycles | 0 | Estimated heat cycles | 0 |
| 16 | | | | | | |
| 17 | Tape contamination (%) | | Tape contamination | | Tape contamination | |
| 18 | PE based | 3 | PE based | 0 | PE based | 0 |
| 19 | cellulose | 0 | cellulose | | cellulose | |
| 20 | PVC | 0 | PVC | | PVC | |
| 21 | | | | | | |
| 22 | Dirt contamination | 5 | Dirt contamination | 0 | Dirt contamination | 0 |
| 23 | | | | | | |
| 24 | Results | | | | | |
| 25 | Mixture: | | | | | |
| 26 | MFI | 0.66 | | | | |
| 27 | UTS | 27.78 | | | | |
| 28 | Elongation at failure | 49.80 | | | | |

Figure 8.6 Screen shot of the input spreadsheet of the model.

### Scenario 1: supermarket LDPE with high dirt levels and multiple heat processing cycles

This would be typical of film that was to undergo a series of processing cycles at the plant and had originated from the consumer domain such that it had picked up a fairly large amount of contamination. In this case the scenario involved three heat processing cycles and 10% dirt addition by mass. Results are shown in Table 8.3

Table 8.3 Model results

| Property | Change |
|---|---|
| UTS | Increase of 19 MPa (62% change) |
| Maximum elongation | Decrease of 11% (30% change) |
| MFI | Decrease of 0.4 g/10 min (75% change) |

The most significant change is for melt flow index, which shows that the material would become more viscous in the melt phase. The UTS shows an increase and the elongation a decrease, implying increased brittleness of the recycled material. The resultant material would become increasingly difficult to process after it had undergone the 3 intended heat cycles.

**Scenario 2: one-use LDPE with moderate dirt and PP tape levels**

This would be typical of film from commercial sources that has been used for packaging as there is a moderate amount of dirt and tape contamination, of 5% dirt contamination and 3% tape contamination. This material would be subjected to a single heat processing cycle, for example pelletisation only.

Table 8.4 shows the results of this scenario.

Table 8.4 Model results

| Property | Change |
|---|---|
| UTS | Increase of 6 MPa (30% change) |
| Maximum elongation | Decrease of 39% (43% change) |
| MFI | Decrease of 0.4 g/10min (33% change) |

The biggest change is for elongation, due a stiffening effect from the dirt and tape contamination. The MFI showed a large decrease, as would be expected with the types of contaminants present.

**Scenario 3: previously recycled (Erema-type) film with light PP tape and heavy HDPE levels**

This scenario would be an example of recycled, mixed polyethylene film, involving three heat cycles, 3% PP tape contamination and 25% HDPE (supermarket carrier bags) in the mixture. Waste recycling from municipal sources would be typical of this composition once it had been washed. The results are shown in Table 8.5.

Table 8.5 Model results

| Property | Change |
|---|---|
| UTS | Increase of 12 MPa (68% change) |
| Maximum elongation | Decrease of 32% (41% change) |
| MFI | Decrease of 0.5 g/10min (46% change) |

The decrease in MFI is more due to the addition of the HDPE than other factors. It is interesting to note that in this scenario the UTS has increased, i.e. the material is stiffer, again due to the presence of the HDPE in the mixture. In a realistic scenario, the resulting material would be matched to an application of rigid plastic, for example as recycled plastic lumber.

## 8.7 Overall accuracy

The model was run and tested with a number of input scenarios as listed in Section 8.6, and including other experimental data taken from Chapter 6. This was done to see how the resultant crystallinity varied in comparison to the measured crystallinity values from experimental data.

It was found that the accuracy of the model output varied between 5% and 15% for UTS and MFI, but could vary up to 25% accuracy for maximum elongation. This also depended on the simulated life-cycles of the material, with some parameters being more accurately calculated than others for certain life-cycle scenarios. It is understandable that there was a reduction in accuracy when predicting the effect of life-cycle factors on maximum elongation because it has the weakest correlation factor. The results shown in Chapter 6 confirm this as maximum elongation can show a large standard deviation, depending on macro-scale factors, such as large pockets or seams of poorly-mixed contamination in the mixture.

Using linear relationships to model the effect of life-cycle factors added inaccuracy to the final results, since many of the relationships between crystallinity and life-cycle factor were not linear. More complicated relationships based on higher-order or logarithmic curves made the model unstable at higher values of life-cycle factors. Using linear trends maintained simplicity of the calculations, which led to more consistent results.

## 8.8 Summary

A unique predictive model for estimating the changes in physical properties of polyethylene film based on life-cycle factors illustrated in this chapter was developed. This model can be applied to analysing the input at a recycling facility to estimate the physical properties of a batch of materials based on their properties on delivery. The inputs to the model were selected based on importance to the recycler, because material condition, mixture and contamination are principal factors in film recycling. This original model is relevant to an industrial process because it allows a recycler to estimate the suitability based on resultant material properties of a recyclate batch prior to processing, which saves on costs.

Crystallinity has been shown to be a reliable property used in determining the change in mechanical properties of the polyethylene by numerical techniques. It was inherently governed by molecular properties such as molecular weight and polydispersity, but these properties themselves are less reliable as they can contribute to mechanical properties in different ways, as discussed in Chapters 2 and 6. Since the molecular factors such as weight and polydispersity determine the crystallinity, it can be treated as a reliable indicator as to the resultant properties of the mixture. Although crystallinity was difficult to measure and requires specialist equipment, it can be reliably interpolated using the MFI and UTS of the material, which are properties that are fairly straightforward to measure.

In order to improve the model more data could be gathered as to the different properties of polyethylene film compounds and further studies of the effect of life-cycle factors. This would allow for more realistic correlations between crystallinity and physical properties. With a larger database of physical properties linked to crystallinity, the coefficient of correlation values could be improved, which would give a more realistic idea of the true accuracy of this method.

More data on molecular weight would also be helpful in finding the model's reliability. Such data could allow for more robust correlations, leading to a more accurate prediction of maximum elongation, which is the least accurate using purely a crystallinity based version.

Acceptable mechanical property changes would be at the discretion of the film recycler. This would depend on the required properties of the product being produced at the plant in question, or the standards that the product must meet. This model can calculate such ranges, but their details would be specific to the individual recycling operation in question, which would involve studying a large number of recyclers to find their individual recycler, beyond the scope of this work.

This model would be best applied to determining the resultant MFI of a material batch in order to inform the recycler when a batch should be alloyed with a less viscous material or if the batch should be rejected altogether. Although dependent on the process at the plant and the end-product, the recycler could have a chart of acceptable MFI ranges and advice of what to do with the material depending on which range the material lies, after being processed by the model.

# Chapter 9 – Economic modelling

## 9.1 Introduction

This chapter is concerned with developing a novel tool to estimate whether a plastic film recycling scheme would be a viable business operation in a realistic market scenario. The experimentation, data and reviews previously presented in this work cannot be put into commercial practice unless there is a sound financial application for any film recycling operation. Hence a crucial step is to model the financial performance of such a scheme in order to anticipate the economics of large-scale film recycling.

The use of economic modelling in waste management and recycling scenarios has been practised previously for both waste collection and recycling operation analysis [10, 92]. Such work however has not looked at the whole process form collection of the waste, reprocessing and re-distribution into a new market. The purpose of the model presented in this chapter was to cover the whole economics of a film recycling operation including the transport logistics, which can be critical for a material with such a low bulk density, as discussed in Chapter 1.

The model used herein was designed to provide data on a theoretical collection, processing and re-distribution operation. The three stages were analysed separately but also linked such that an event during one stage could be allowed to affect the performance of another, as would be the case in an actual recycling operation. The model could then re-assess for such an effect. For example the delay effect on the re-distribution economics if there were a contamination problem in the processing stage could be investigated.

The model was also run in conjunction with a computer-controlled loop (or macro) such that a large number of characteristics could be automatically calculated, giving a more accurate representation of the effect of altering the input parameters. This was found to be very useful for finding regions of economic feasibility that might normally have taken a long time to determine. Data output was either numerical for running individual cases or presented in graphical format when the effect of varying certain parameters was examined.

## 9.2 Model inputs

The novel model comprised of a number of panes in a computer spreadsheet. Data was input into the first pane of the spreadsheet, which was then used to feed the model parameters as detailed in Section 9.4. The model had 41 inputs, split into the 7 major fields given below:

1. Amounts of plastic film waste available in region covered for study.
2. Details of collection vehicles: capacity, range, mileage, running cost and staff.
3. Amounts of film input: multiple customers, variable contract prices.
4. Plant operation: day and shift patterns, staff numbers.
5. Plant costs: leasing, services, equipment, maintenance.
6. Amounts of film output: multiple customers, variable contract prices.
7. Haulage of product: transport routes, costs, vehicle capacity.

## 9.3 Model outputs

The aim of the model was to return financial data for a working plant, but there were other intermediate statistics that were key in verifying whether the model was providing realistic information. These intermediate outputs were used to calculate variables such as the size of the delivery operation required based on the plant output. For example, should the plant production rate exceed the capacity of the delivery vehicle, another vehicle would be factored into the transport costs. The model outputs included the following:

1. Staff and machine work and sorting rates, including overall film production rate.
2. Costs: collection, sorting / processing, redistribution, waste disposal.
3. Total cost, per year and per tonne.

## 9.4 Processing procedure

### 9.4.1 Introduction

There were three main calculation steps in delivering the model results, namely the econonomics of collection, process and distribution. Figure 9.1 shows a schematic of the computational model with data flows expressed by arrows in the diagram. The blue arrows indicate primary information flow, which was input into the model by the user (yellow box). Red arrows indicate seconday information flow, where the model generated data that was fed into other inputs in order to calculate subsequent parameters, an example of this would be the number of vehicles required to haul the specified amount of waste input. Data flow into the final calculations is indicated by the black arrows.

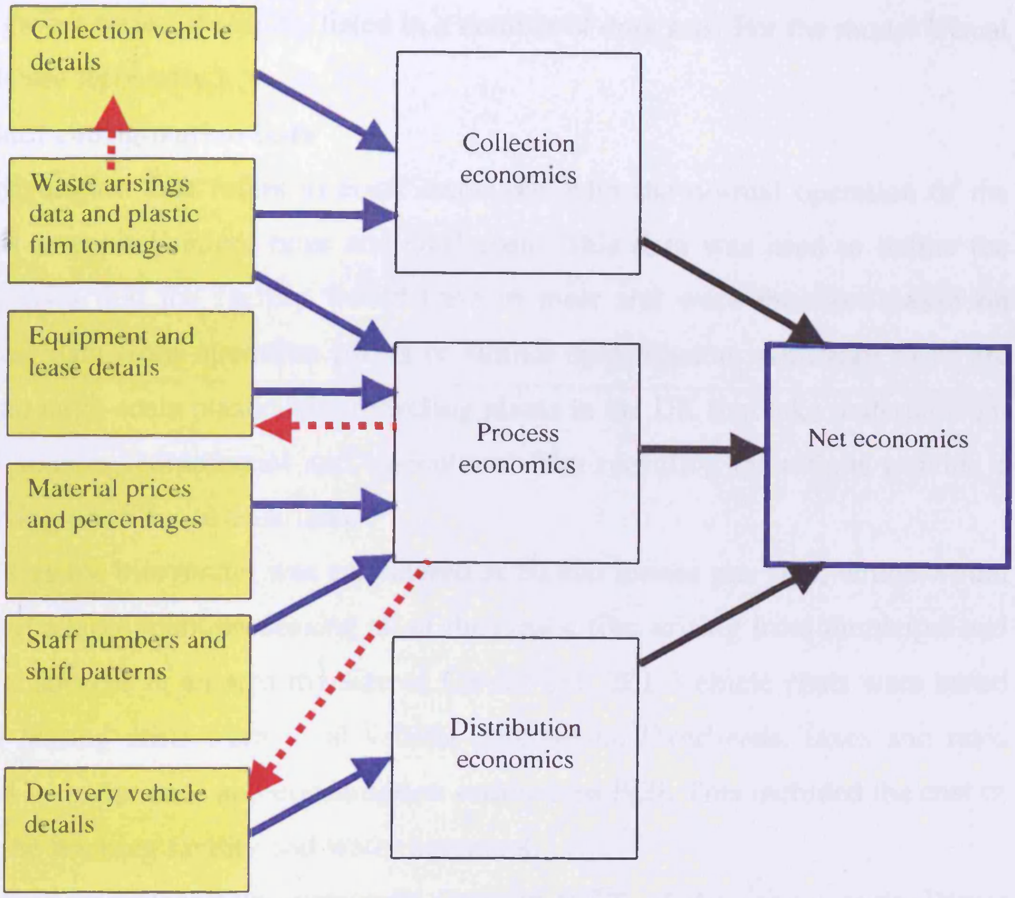


Figure 9.1 Schematic of the modelling process

The output of each stage was visible in the spreadsheet such that any output parameters could be checked for consistency. In order to return the net economics of the whole process, the model was prepared as a dynamically-linked spreadsheet over a series of sub-routines to calculate data using the following steps:

1. Input all data pertaining to process (as listed above).
2. Calculate economics of collection system.
3. Calculate process economics and equipment performance.
4. Calculate economics of product distribution system.
5. Sum net economics based on steps 1 – 4.

As there were a number of scenarios run (almost 50 for this investigation, each containing 100 points) it was decided to program a macro to run the data. Once the spreadsheet was programmed and verified for correct operation a stepwise macro was written in Visual Basic to input the model with a series of data and output the results in a matrix, rather than the operator running large amounts of scenario data manually.

This was done to make the model run quicker but also to allow for a greater number of data points to be collected from the model. A two-dimensional loop structure was used that gave a series of results, listed in a number of data sets. For the model Visual Basic code see Appendix J.

### 9.4.2 Plant configuration data

Plant configuration data refers to costs associated with the normal operation of the plant, such as capitalisation, rates and staff costs. This data was used to define the major expenses that the facility would have to meet and were therefore based on existing real data from operation plants of similar specification. Although there are currently no large-scale plastic film recycling plants in the UK that take material from municipal sources, commercial and agricultural film recycling operations provide a useful starting-point for calculations.

The plant size for this model was considered at 20,000 tonnes per year, which would be typical of a large plant processing all of the plastic film arising from municipal and commercial sources in an area the size of Cardiff [11, 20]. Vehicle costs were based on typical leasing costs from local vehicle contractors. Overheads, taxes and rates were based on experience and consumption estimations [92]. This included the cost of operating the washing facility and water treatment.

Maintenance and replacement parts were factored at 5% of the capital costs. Power consumption was based on 560 kW, factored with energy costs of 8 pence per kWh. This was based on previous data gathered from a plant of similar design [10]. Labour costs were based on man-hours and a charge-out rate of £15 per hour for factory-floor staff and £30 per hour for management. Landfill costs were £30 per tonne including landfill tax. Landfill tax is due to increase in the future as per European legislation [24], so the model was capable of varying landfill tax as required.

Capitalisation of the plant was based on £2.5 M, repaid over 20 years via a mortgage-type arrangement at 6% annual interest. Plant costs were also adapted from previous studies on this subject [10]. Plant costs included the provision of the washing facility. Ground leases, taxes and other rates were set to £100,000 per year. Inflation was not factored into the model in order to preserve simplicity.

### 9.4.3 Collection economics sub-routine

Figure 9.2 shows a schematic of the sub-routine used to calculate the collection economics. Model inputs are marked in yellow boxes, whereas calculated parameters are in white boxes. The main output from this sub-routine was termed the "collection income" because under some economic conditions the collection operation would make a profit from the waste supplier by charging a sufficiently high gate fee to cover the collection infrastructure. This would be more likely should the plant qualify to issue Packaging Recovery Notes (PRNs).

To calculate the number of collection vehicles the model took inputs from the amount of waste to be collected per time period in question (nominally days), the number of collections per period and the capacity of the collection vehicle. This value was then used to calculate the labour and fuel costs, along with distance travelled per period and labour required per vehicle, which would be dependent on the specification of the collection vehicle used.

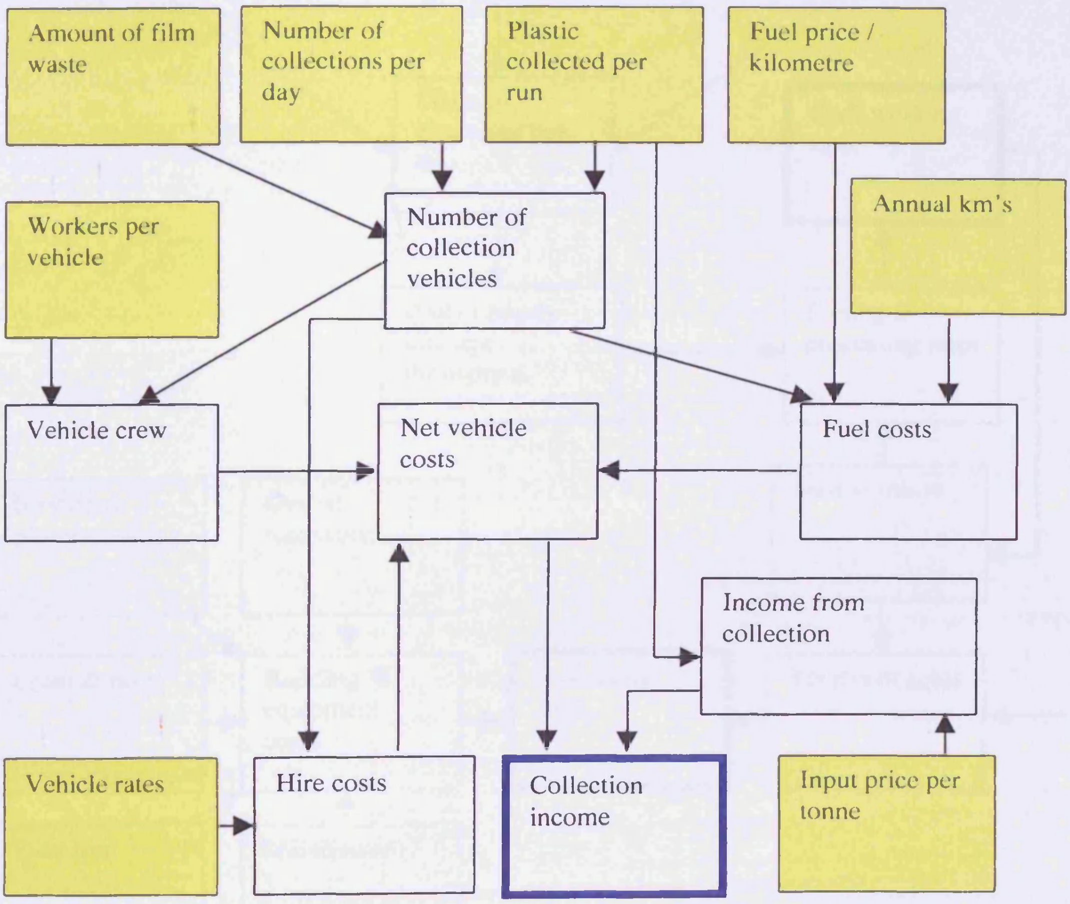


Figure 9.2 Schematic of the collection economics sub-routine.

Net vehicle costs were found using labour, fuel, and hire costs (including insurance and charge-out rate of vehicle supplier). The net collection economics were then found using the net vehicle costs and the income generated from the collection, which was in turn dependent on the contract price agreed with the waste producer. Thus this assessment would determine the profit or loss environment.

### 9.4.4 Processing economics sub-routine

Figure 9.3 shows a schematic of the sub-routine used to calculate the processing economics. The amount of material processed by the plant per time period was calculated from the amount of waste delivered to the plant, the yield (recoverable portion of this waste) and the daily operating hours of the plant. This calculated value was used to return the plant tonnage throughput.

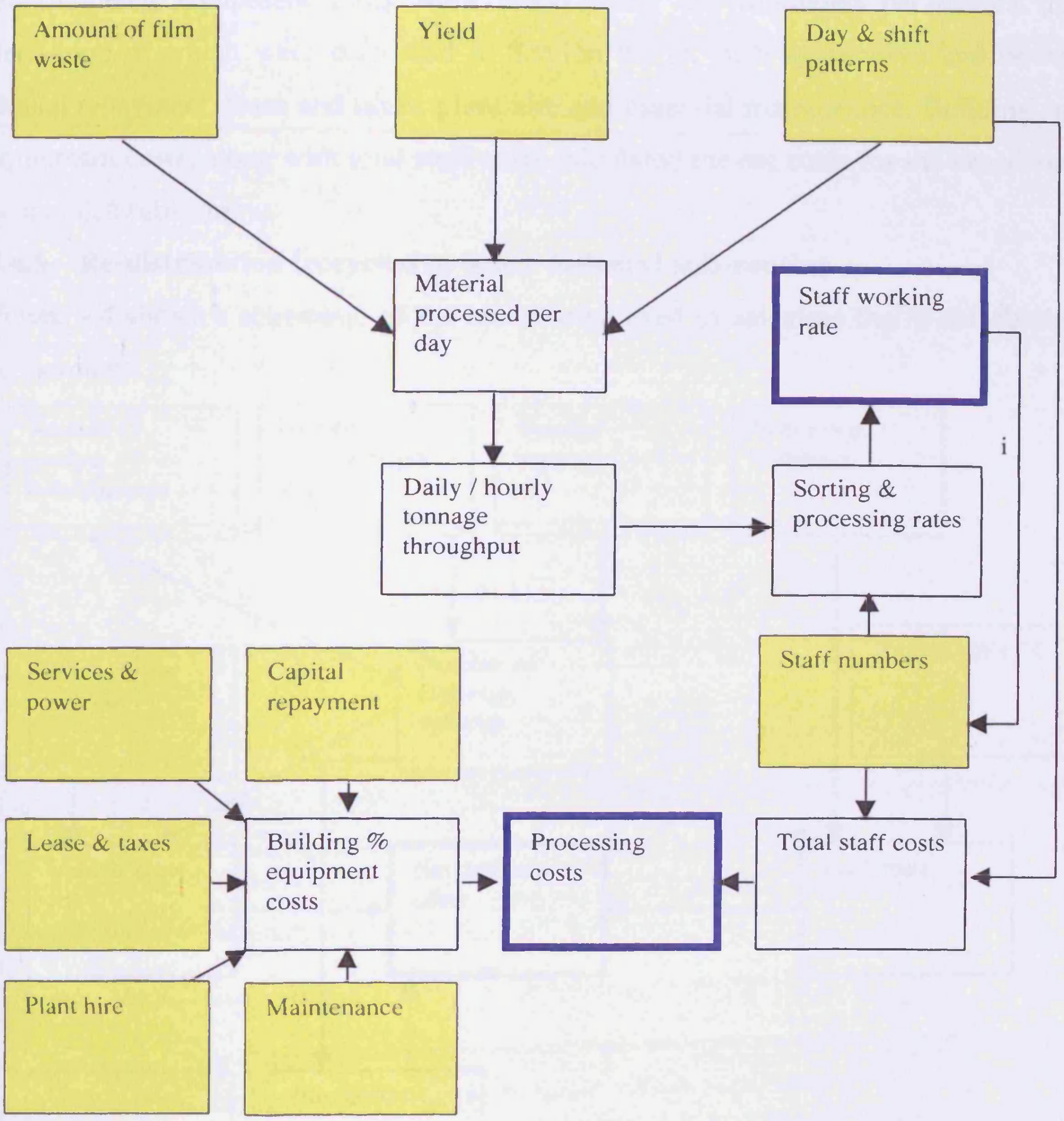


Figure 9.3 Schematic of the processing economics sub-routine.

The sorting and processing rates were calculated by using the tonnage throughput divided by the number of staff sorting and processing the material, which in turn found the staff working rates (in tonnes per hour). Since staff working rates could vary depending on plant design and end product, it was placed into a user-defined loop, so that the user could vary the staff numbers, in conjunction with the plant throughput to find a desired work rate. This was useful because otherwise the model would either have to stipulate staff numbers or staff work rate, but by letting the user optimise the work rate gave more flexible control on human resource costs and performance. With staff numbers optimised by the user, total staff costs were found in conjunction with the shift patterns specified earlier.

Building and equipment costs were found using the following parameters (the derivation of which were discussed in Section 9.4.1), such as services and power, capital repayment, lease and taxes, plant hire and essential maintenance. Building and equipment costs, along with total staff costs calculated the net costs for the processing economics sub-routine.

### 9.4.5 Re-distribution (recycled product delivery) sub-routine

Figure 9.4 shows a schematic of the sub-routine used to calculate the re-distribution economics.

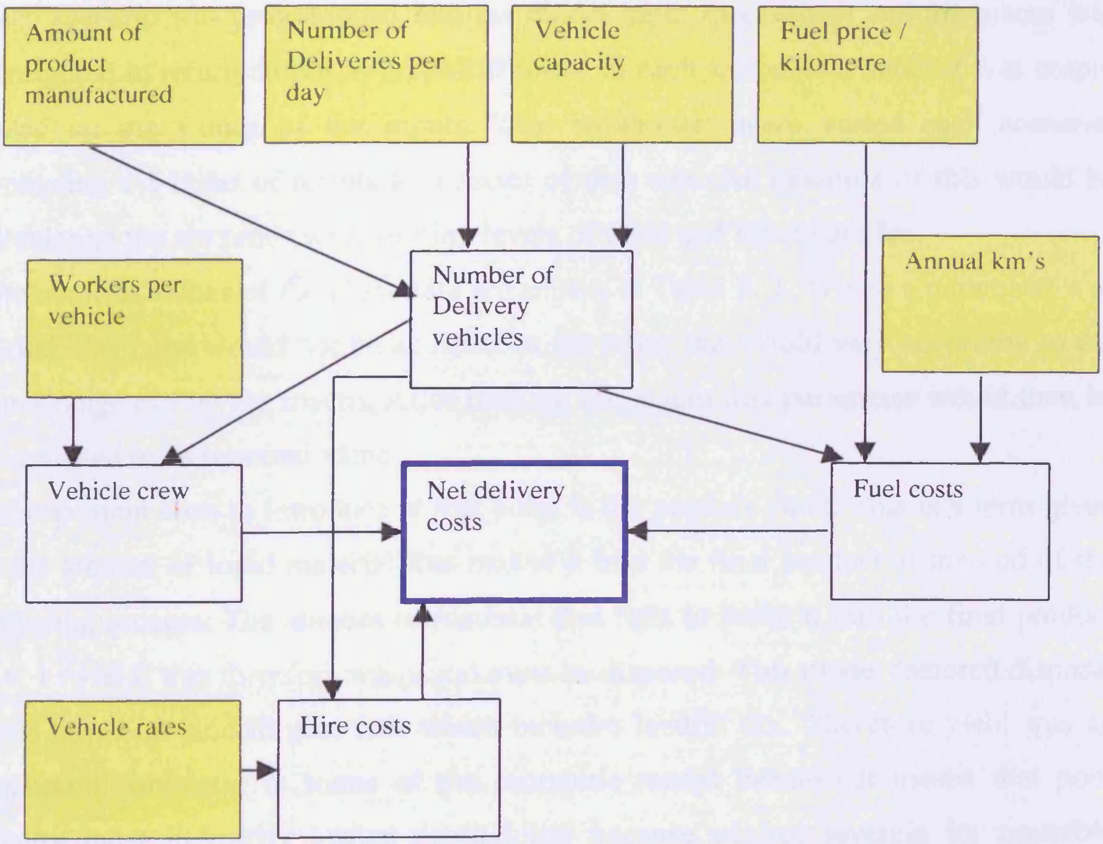


Figure 9.4 Schematic of the re-distribution economics sub-routine.

To determine the number of delivery vehicles the model took inputs from the amount of waste to be delivered per time period in question, the number of deliveries per period and the capacity of the delivery vehicle. This value was then used to calculate the labour and fuel costs, along with distance travelled per period and labour required per vehicle, which would be dependent on the specification of vehicle used. Net delivery costs were found using labour, fuel hire costs (including insurance and charge-out rate of vehicle supplier).

## 9.5 Scenarios investigated by the model

It was decided that the model should look at 4 scenarios which would be of interest to an investor seeking to assess the feasibility of a recycling plant. These scenarios were briefly defined as:

1. Product yield and input material gate fee for a range of material selling prices.
2. Product yield and selling price for a range of input material gate fees.
3. Product yield and collection vehicle capacity for a range of material selling prices.
4. Sales cost and gate fee for a range of product yields

Each scenario was programmed into the model input spreadsheet and the macro was configured to return output in graphical form. In each scenario, a data set was output based on the values of the inputs. Two parameters were varied each scenario, producing a 2-D set of results as a series of data sets. An example of this would be calculating the net profit with varying levels of yield and input gate fee.

The nominal values of the plant data are shown in Table 9. 1. Where a parameter was varied, the value would not be as listed in the table, but would vary according to the input range run by the macro. After running the macro this parameter would then be re-assigned to its nominal value

An important term to introduce at this point is the product yield. This is a term given to the amount of input material that makes it into the final product at the end of the recycling process. The amount of material that fails to make it into the final product (i.e. 1 - yield) was therefore waste and must be disposed. This model factored disposal costs based on landfill gate fees which includes landfill tax. Therefore yield was an important parameter in terms of the economic model because it means that poor quality input indirectly lowers profitability because of lost revenue for unusable material and, more significantly, the extra costs of waste disposal.

Table 9. 1 Nominal values of model parameters used to investigate the four different scenarios.

| Parameter | Nominal value | Units |
|---|---|---|
| **Plant details:** | | |
| Amount of plastic film for collection | 20,000 | Tonnes |
| Yield | 66 | % |
| Number of shifts/day | 2 | |
| Days operational per week | 5 | |
| Net collection price per tonne | 20 | £ / Tonne |
| Net selling price per tonne | 100 | £ / Tonne |
| Staff required (sorting + screening) | 4 | |
| Staff required (processing) | 4 | |
| Managers | 2 | |
| Building lease / repayment | 100,000 | £ / year |
| Services, power, taxes | 350,000 | £ / year |
| Equipment capital repayment | 250,000 | £ / year |
| Plant hire (forklifts, skips, etc) | 10,000 | £ / year |
| Essential maintenance | 12,500 | £ / year |
| **Delivery vehicle details:** | | |
| Annual distance travelled | 25,000 | Kilometres |
| No. workers per vehicle | 1 | |
| Insurance per year | 4,000 | £ |
| Hire costs per week | 250 | £ |
| Plastic hauled per run | 25 | Tonnes |
| Number deliveries per day | 2 | |
| **Collection vehicle details:** | | |
| Annual distance travelled | 25,000 | Kilometres |
| No. workers per vehicle | 1 | |
| Insurance per year | 4,000 | £ |
| Hire costs per week | 250 | £ |
| Plastic collected per run | 9 | Tonnes |
| Number collections per day | 2 | |

The potential impact of the scenarios considered can be described as:

**Scenario 1** **Product yield and input material gate fee for a range of material selling prices.**

This was undertaken to examine the relationship between the prices of the waste material entering the plant and the recycled product, in conjunction with the effectiveness of the plant. In this scenario the selling price of the recycled material was the most important factor and results showed the effect of varying this value in terms of plant profitability.

**Scenario 2** **Product yield and selling price for a range of input material gate fees.**

Similarly to scenario 1, by examining the input and output effects, but concentrated on the price paid for the waste material entering the plant. Profitability was therefore more dependent on the source of the material.

**Scenario 3** **Product yield and collection vehicle capacity for a range of material selling prices.**

This scenario was run in order to show the effects of vehicle selection versus plant performance and profitability. Although vehicle specification may seem less significant in comparison with the overall operation of the plant, when considering a low bulk density material such as plastic film it was important to understand haulage capacity and select the optimum vehicle size for the required plant throughput.

**Scenario 4** **Sales cost and gate fee for a range of product yields.**

This was undertaken to show how the material yield affected the financial performance of the plant. As mentioned earlier, yield was dependent on purity and process efficiency. Therefore understanding how this affects the finances of the plant was essential. For an investor, it would be important to know the point at which material contamination places such a burden on the process that the plant will not make sufficient financial returns.

## 9.6 Results

### 9.6.1 Introduction

The results are shown based on the macro output of 100 data points per series. Individual data points are not shown as they are close together and the trend line though them expresses the relationship more clearly. Nominal data values are as expressed in Table 9. 1.

### 9.6.2 Scenario 1, product yield and input material gate fee for a range of material selling prices.

Figure 9.5 shows the relationship between overall profit and processing yield. The series (coloured lines) on the graph correspond to different gate fees charged for accepting the waste material. Where the value is negative, this means that the plant is purchasing the plastic film waste from the waste producer, rather than being paid to take it away. The sudden but slight reduction in the traces at 65% yield corresponds to plant output increasing above the capacity of the delivery vehicle, thus causing another vehicle to be leased, which causes to overall profit to decrease suddenly due to the effect of running another vehicle. Calculations based on smaller vehicles had a larger number of discontinuities in the data as more vehicles had to be leased.

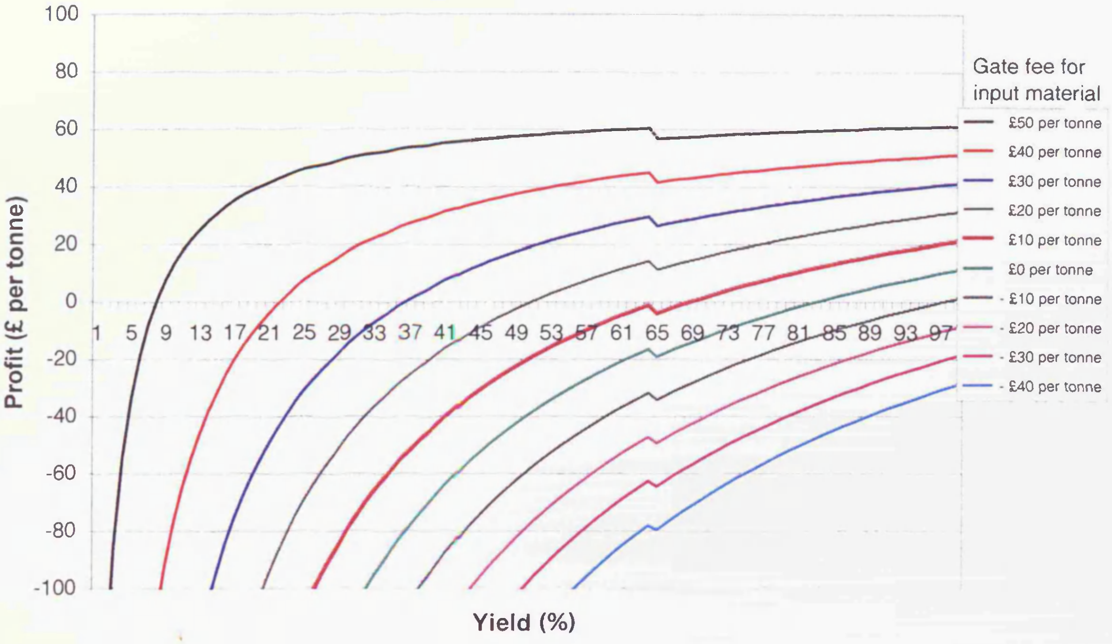


Figure 9.5 Relationship between yield and profit for different gate fees for scenario 1.

The series of curves shown in Figure 9.5 highlights a non-linear relationship. As the gate fee increases the curves become more pronounced and a “knee” is formed. This is clearly shown for the £50 per tonne line. It is also worth noting that as gate fees increase there is a substantial reduction in the yield for break-even conditions. Furthermore, for the higher gate fees, the change in profit per tonne is less significant as yield changes to such an extent that for a gate fee of £50 per tonne and for a process yield of greater than 40% there was little change in profit. In process terms this was a unique situation such that other operating factors had more of an impact.

In terms of the effect of gate fee on performance, a negative fee of less than (i.e. the plant operator paying more than) £10 per tonne of waste would rarely give a financial return. At £0 per tonne, the break-even point is around a yield of 82%. Figure 9.5 shows that the differences between gate fees become larger with increasing fee. Therefore it would be advisable to negotiate as high a gate fee as possible with a waste supplier, even if this means a slight decrease in purity levels.

### 9.6.3 Scenario 2, product yield and selling price for a range of input material gate fees.

Figure 9.6 shows the relationship between yield and profit over a range of different product selling prices. This was gathered running the model with the same conditions as previously highlighted but a constant gate fee of £0 per tonne, which is realistic in a modern recycling scenario. Although the relationship seems similar to the case of the gate fee data, the individual series are far closer together. The increased delivery vehicle cost due to greater product manufacture is also seen as a discontinuity in the data at around 65% yield.

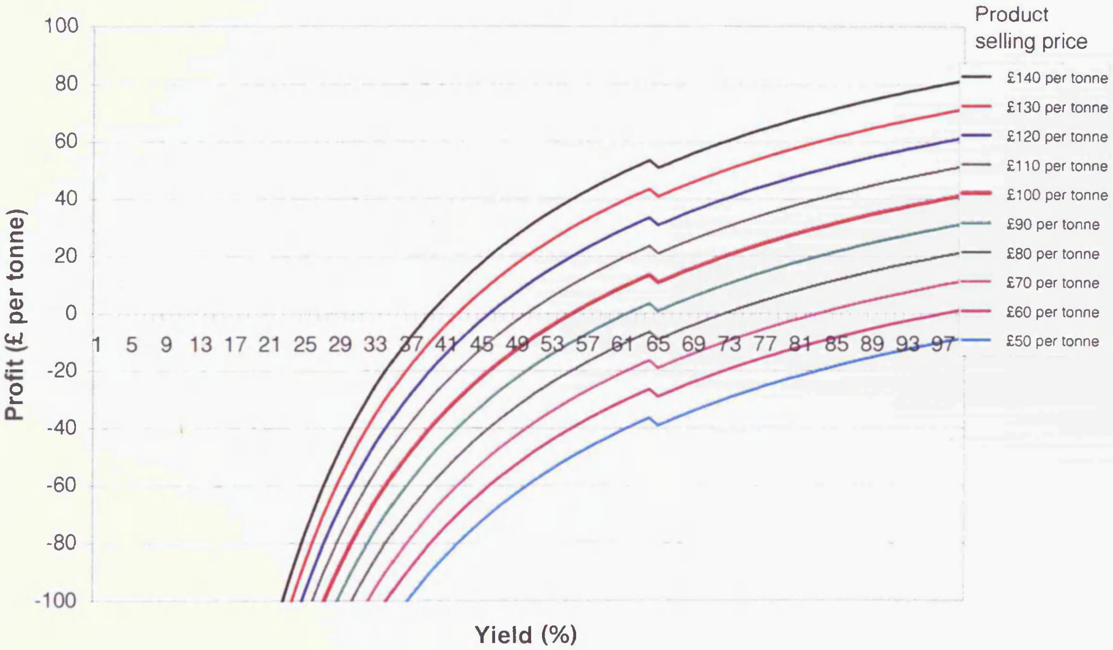


Figure 9.6 The relationship between yield and profit for different material selling prices for scenario 2.

Again a non-linear relationship was observed. The series of curves had a reasonable parallel uniformity. In this scenario yield had a significant effect on the break-even point. This varied from 37% at a selling price of £140 per tonne to 97% for a selling price of £50 per tonne. The shape of the curves also highlight that the gradient reduces, thus lessoning the effect of selling price on profitability.

The data shows that for a realistic yield of around 65%, it is advisable to sell the product for at least £90 per tonne although this would leave little margin for error or decrease in yield levels. For a good selling price of £140 per tonne, the breakeven point is around 40% yield thus more contamination could be accepted. The shape of the data implies that by changing the selling price by £10 per tonne (i.e. from one series to the next) will effect profitability depending on what the selling price was originally. Thus, profit increases are more favourable at the higher end of the selling price scale. It would be more advisable to improve yield if the selling price were low.

### 9.6.4 Scenario 3, product yield and collection vehicle capacity for a range of material selling prices.

Figure 9.7 shows the economic effect of varying the collection vehicle capacity on the profit. This scenario was run with a gate fee £0 per tonne of and a selling price of £100 per tonne with variable yield. It is interesting to note the more profound effect that varying this parameter has on the profit.

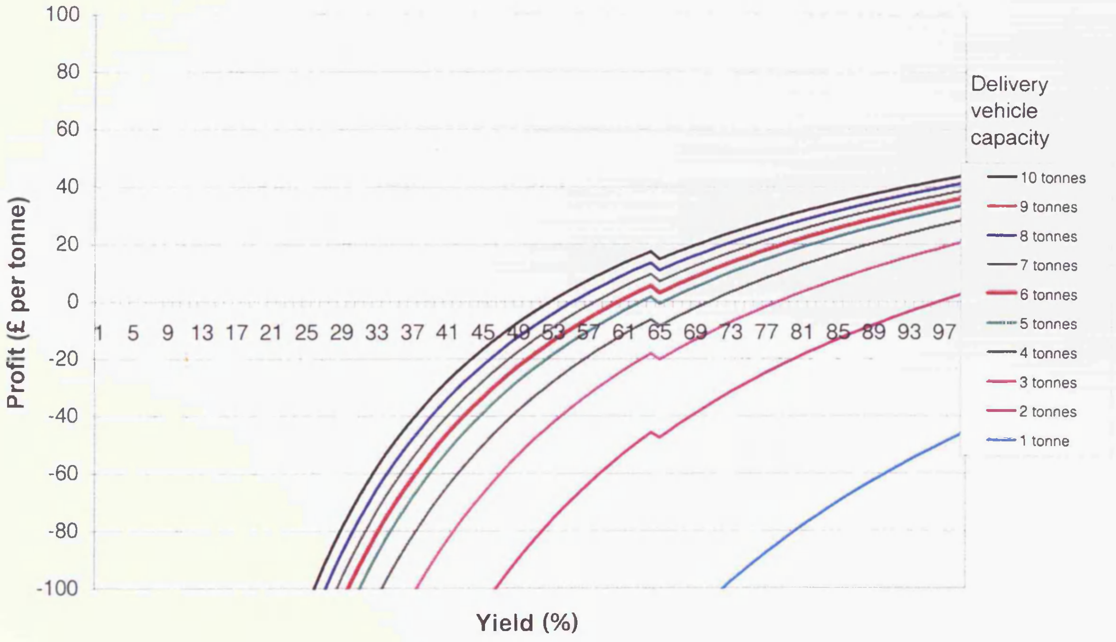


Figure 9.7 Relationship between yield and profit for a range of collection vehicle capacities for scenario 3.

As expected the responses shown in Figure 9.7 are non-linear and similar to that identified in Figure 9.5 and Figure 9.6. There is no distinctive "knee" to the curves and it is also apparent that above a vehicle capacity of 5 tonnes the lines are more closely packed. This suggests there is less of an impact above the 5 tonne capacity. The impact of yield is less pronounced at the break-even point, varying from 52% for a 10 tonne vehicle capacity to 62% for a 5 tonne capacity. Below 5 tonne delivery vehicle capacity the size of the vehicle has a major influence.

The data shows that maximising vehicle capacity is an important part of maintaining collection economics. This promotes the idea that compaction is crucial to any film collection scheme otherwise economics will suffer as a direct consequence of poor vehicle loads.

### 9.6.5 Scenario 4, sales cost and gate fee for a range of product yields

Figure 9.8 shows the relationship between sales price, gate fee and profit, based on a yield of 66%. This graph shows the overall financial performance of a film recycling facility running at a constant rate. The response is linear and the series lines are parallel, highlighting symmetry across the gate fees analyses. It is also observed that gate fee had a crucial effect on the break-even selling price. Note that the x-axis is product sales price not yield.

Figure 9.8 Sales price versus profit with varying gate fees for scenario 4.

The graph shows that for gate fees above £50 per tonne the facility will almost always be profitable because of the money made in receiving the waste, but the amount of profit will be dependent on yield. Conversely, paying greater than £10 per tonne for the material makes the facility unprofitable over all realistic selling prices. Recycling highly contaminated waste is very difficult, as shown earlier, therefore a facility dealing in such material would be less likely to make a product and could run the risk of losing its ability to issue PRNs if insufficient recycling is performed.

At a gate fee of £0 per tonne the facility's breakeven point is around a sales price of £90 per tonne at 66% yield. With a selling price of around £130 per tonne, the facility could expect to generate £ 0.5 million per year if input was 20,000 tonnes.

## 9.7 Summary

The financial model presented herein has shown that it is possible to determine the feasibility of a plastic film recycling operation given the appropriate inputs. The model can highlight envelopes of feasible operation based on the size, quality, proximity and cost of the waste material used to make a new film product. The model could also be used to determine the effects of a change in the day-to-day running of a recycling plant, for example taking-in an unusually contaminated waste input, or negotiating a new contract price for the recycled product.

The results show that a film recycling plant was feasible provided the economics are kept to within certain parameters, which are interdependent. Management of such a facility should bear in mind that gate fees and product selling prices can have a significant effect on the overall profitability of the operation, but also that there are other, non-financial parameters, such as yield, and staff working rates that can seriously affect performance.

Proximity was a key issue when dealing with film recycling. As modelling data has shown, the amount that a collection vehicle hauls in a typical day can determine whether or not a recycling business will succeed. It was therefore pertinent to analyse the intended area for the facility and determine the input haulage costs. Coupled with this, the actual vehicle capacity or its compaction ability should be considered simultaneously. As the results have shown, haulage costs should be minimised wherever possible, which is likely to mean compaction when dealing with waste plastic film.

Recycling yield is a critical parameter, according to the results. It was interesting to note that the effect of increasing the product yield enhances the profitability, but this is in turn dependent on the gate fee and selling price of the material. In some situations, such as when the yield is very high, it might be advisable to look for financial gains in ways other than increasing the yield further.

Product distribution has an effect on the overall profitability that generally seems small in comparison to effects such as yield. This was not the case when the operation was running at a position near to the capacity of a transport vehicle. Should the plant yield cause the product to exceed the capacity of a vehicle it would not be advisable to use an extra vehicle to haul the excess product, as this will effect profit. It would be more sensible to stockpile material and dispatch when the stockpile is close to that of a full load.

# Chapter 10 – Summary of impacts of investigation

## 10.1 Overview of industrial impact

### 10.1.1 The plastic film recycling industry

Analysis of waste arisings and recycling capacity has shown that a substantial deficit is still in existence between the amount of plastic film waste produced in the UK and the recycling capacity from reprocessors. With a recycling capacity of 0.25 million tonnes per annum and a waste arisings of 2.5 million tonnes per annum, major investment is therefore needed in the recycling infrastructure to meet the potential market demand [75]. Such investment will not be forthcoming without reliable evidence that plastic film recycling is a viable business opportunity, even in the light of predicted increases in Landfill Tax.

This investigation has shown that a possible solution to address this lack of investment would be the construction of a trial plant specialising in recycled products from a number of waste film sources. This would act as an illustrative demonstrator to investors to prove that plastic film recycling is a practicable business opportunity.

Proximity is still a major issue to the UK recycling infrastructure. This investigation and related publications has shown that most plastic recycling businesses are gathered around the M6 motorway, as this North-Western region of England has traditionally been an area where plastic production is a major industry [22]. It is therefore logical that many reprocessors have grown out of this area [4]. Waste from non-manufacturing sources, however is generated across the country, mostly in heavily urbanised zones. As mentioned in Chapters 1 and 9, proximity is key when transporting such a voluminous material. The management of transfer stations and the location of recycling plants is therefore a very important issue when dealing with this material.

Another potential barrier from within the industry is confidentiality when discussing manufacturing techniques. It is unlikely that recyclers would share technology as production processes are seen as proprietary information. This could slow down the progression from the current industry position.

This investigation has highlighted that current plastic film recyclers should consider the impact of utilising materials that have higher contamination levels than their current feedstocks. Should the market increase for recycled plastic film with greater effects from life-cycle factors, recycling plants should have a broader understanding of these factors if they wish to expand on future business opportunities. Such opportunities are far more likely to come from feedstocks that have been exposed to the consumer domain.

### 10.1.2 Market potential of recycled plastic film products

A major drawback associated with low-value recycled plastics is market applications. In the case where a plastic waste is down-cycled, the recycled product is of a much lower value, and will generally have a single application. A good example of this is the case where plastic film is recycled into plastic lumber profiles. The market and applications for plastic film is many times larger than that for plastic lumber, hence supply is far greater than demand.

The market potential for recycled film in terms of damp-proof membranes and agricultural sheet is close to saturation [4]. There is however a multitude of applications that have not been exploited, for example consumer goods packaging. Given that 36% of all plastic in the UK is used in packaging applications, there is a real potential for introducing recycled film. Food packaging will present problems with issues such as hygiene and appearance, and work must be done to address such issues before the market can be exploited. Non-food packaging, such as textiles or electrical goods, still represents a large proportion of the packaged goods market.

There are also markets for recycled packaging in secondary and tertiary applications, such as carrier bags, pallet strapping or pallet wrapping film. These are emerging markets that have a market share of around 30% recycled material [11]. As appearance is not such a priority as in the case of direct consumer packaging, secondary and tertiary markets would be a useful market for recycled films to break in to. This should create links into the consumer packaging domain, which could make the transition to recycled consumer packaging easier. Some of these markets are in existence in developing countries (China for example), although their throughput and production rates have so far been too difficult to quantify.

## 10.2 The relevance of the thesis investigation in the context of the film recycling industry

### 10.2.1 Experimental testing of life cycle factors

The current state of the industry focuses on avoiding degradative life-cycle factors such as heat cycling or contamination at all cost. It is apparent that no company is aware of the actual qualitative affect of these factors, otherwise there would be physical acceptability thresholds for waste material, rather than relying on instinct alone. The results from this work show that such evaluation could be done in a more scientific manner than this.

Many of the results presented herein apply to rigid plastic products as well as film. The physical affects of the life-cycle factors have been identified on both a crystalline and molecular level, therefore the theory behind the changes in mechanical properties should apply to similar kinds of plastic products, for example rigid HDPE milk bottles. It is assumed that plastics recycling will become commonplace in the future and this baseline data will prove useful when evaluating material suitability for recycling.

Other data from the results show that it is not a simple matter of downgrading the physical properties (e.g. UTS, elongation or MFI) of a plastic waste source in order to determine its properties post-recycling. The recycler will still have to make assumptions on the morphology of the blend (i.e. percentage crystallinity) or perform XRD and GPC measurements. This will present problems for recyclers because such molecular-level analysis is expensive and requires expertise to operate. The process of evaluating a plastic waste feed for recycling would be made easier if such equipment was less expensive and more user-friendly.

### 10.2.2 Economic modelling

Overall the financial modelling conducted in this investigation has shown that a plant utilising the technologies illustrated is economically feasible, but very dependent on slight changes in operational conditions. When forecasting the performance of such a plant, matters such as potential increases in Landfill Tax should be borne in mind, as potentially this operation could produce large amounts of waste when processing contaminated feedstocks. Should operating conditions lead to an unprofitable performance, the model should be capable of alerting management to this.

The waste industry sees plastic film recycling as only a very small proportion of the total mass of waste that is handled per year in the UK. However, this investigation has shown that plastic film waste can be recycled economically into products that will allow obliged companies and local authorities to meet legislation targets, such as the packaging regulations. Companies engaged in the handling and distribution of plastic waste for recycling should be made aware of the logistical aspects of transporting this material in order to maximise profit and keep costs as low as possible for clients who are required to recycle their plastic film by law.

### 10.2.3 Predictive model for estimating material properties

In terms of application, the experimental and modelling results have shown that it is possible to estimate the condition and properties of a recycled plastic product, based on a few simple tests carried out beforehand. However, this does not necessarily imply that such a system could be employed at recycling plants without difficulty. The ability to estimate the change in physical properties would depend on the ability of an operator to estimate the composition of the feedstock in question. The predictive model adds weight to any estimation made prior to recycling, but it can't be used make definitive judgement on a batch of unknown composition.

The use of this model is therefore limited to a decision-making tool, although without the model decisions would be made purely on instinct, which will undoubtedly vary between operatives. The introduction of the Publicly Available Specification (PAS 103) is a positive step towards the quantification of plastic wastes, which implies that such predictive models may prove useful in enhancing the description of recyclate feedstocks. This model could have an impact on the recycling industry if used in conjunction with PAS103 because it could advise on acceptability limits.

Companies involved with producing plastic recycling equipment could benefit from the application of this predictive model as it gives an idea of what potential future recyclate streams will look like. If an increase in the recycling of contaminated feedstocks is more likely, equipment manufacturers should understand how life-cycle factors will affect plant equipment. Future business opportunities could involve development of more efficient washing and separation processes, recycling systems that can allow for higher levels of contamination and intelligent systems that predict the material properties of feedstocks prior to the expense of processing them.

### 10.2.4 Potential use of recycled drainage media and landfill cover membrane

The Landfill Directive [85] has employed strict criteria as to the design of landfill sites and the nature of the waste that they can accept, post July 2004. According to EA data, there are around 900 landfill sites in the UK at time of writing, consisting of inert, non-hazardous and hazardous wastes [93]. Such statistical evidence would suggest that there is a potentially large market for barrier membrane and drainage media and there is a real value to this investigation. Availability of sufficient material will be a key issue in procurement, i.e. that demand could be met within customer timescales. Landfill projects will require large amounts of drainage and capping material over a relatively short space of time, compared to the actual lifespan of the completed phase, which could be a number of centuries. Since the aggregate must be manufactured, rather than quarried, there could be problems associated with procurement timescales.

There are also political benefits to using the recycled material, namely the positive portrayal of the landfill company. This impact should not be underestimated, because landfill operators are under pressure to maintain a positive environmental image. Although the current standards do not permit the use of recycled material, research such as this can outline the fact that such material can be used in place of virgin feedstock. This could lead to a broader acceptance of recycled material in engineering applications, such as that shown in the construction sector, which could lead to consideration for use in landfill projects.

The required infrastructure for manufacture of the two products would be quite different. Geomembrane production would require a film blowing operation, which would involve a custom-built facility for the separation and manufacture of the film. However, this could be subcontracted to any recycling operation that has the capacity for producing film, such as those currently producing damp-proof membrane, as highlighted earlier in this investigation. The major obstacle would be cleaning the input feedstock to a suitable standard.

Production of the aggregate material would be far simpler, as the process involves far fewer steps and virtually none of the quality control associated with film production. The major problem with the production of the pellet would be locating a facility willing to produce such large fragments of material from such a contaminated feedstock with the potential for damaging production equipment due to harder contaminants. This could result in the need for custom-made equipment that might adversely affect the economics of the process.

## 10.3 Industrial acceptance of the use of recycled films

Industrial acceptance will be subject to proven commercial success. For commercial success any recycled product must be accepted by the manufacturers who must work with the material to produce an end product. Although pressure from consumers for environmentally-friendly goods can be counted as an impetus to produce such recycled goods, it may not be seen as a principal concern to a manufacturer in comparison to more immediate problems such as melt flow index, consistency of feed and mechanical properties of the material.

This investigation has highlighted that one of the main drawbacks with accepting recycled material into a production operation is the lack of a reliable method of auditing the material. Virgin sources can be traced to the original point of manufacture and production, even if this means as far as the oilfield from which the original crude oil used to make the polymer was pumped [2]. This ensures that all plastic products can be clearly audited or traced should quality control problems arise. Recycled plastics from mixed sources cannot be audited any further than the waste source from which they arose, as data on the material batch is normally unavailable prior to the point of waste origin. This can make recycled plastic unpopular with manufacturers because, depending on the application, there can be no quality guarantee for the final product.

It would therefore be logical to implement a guarantee system to act as a way of ensuring the quality of recycled feedstocks. This could be run in conjunction with subsidised large-scale field trials in order to build a track-record for the material, although such trials may not be popular with existing recycling firms that use waste from clean production sources. It is interesting to note that most recycled films would not be translucent, which is a major selling factor of virgin films. Co-extrusion or lamination could give a more aesthetically acceptable product, but there will always be a problem if the contents of the packaging cannot be seen in some applications [32].

# Chapter 11 – Conclusions and recommendations

## 11.1 Conclusions

### 11.1.1 Material cycling

This investigation has shown that there is a link between the changes in polymer structure and the recyclability of plastic film products. Experiments covered in this study have shown that polyethylene materials can degrade when recycled, i.e. they can become stiffer and more brittle. This effect has been attributed to the shortening of polymer chains in the plastic materials. Highly branched polymers, such as LDPE reduce in molecular weight, causing them to become more crystalline, whereas unbranched polymers, such as HDPE, lose alignment and become less crystalline.

As for processing, branched polymers decrease in MFI more rapidly depending on their degree of branching, whereas unbranched polymers can increase in MFI with increasing numbers of heat cycles. These are dependent on the change in crystallinity of the materials when recycled. With all these factors in mind, results indicate that unbranched polymers are more suited to thermal recycling.

Previous research into successive heat cycling of polyethylenes has concentrated either on process conditions, such as the change in MFI, or on investigating molecular structure. This work is novel because it simultaneously investigated changes in mechanical properties, processing properties and the molecular structure of polyethylene materials during successive process heat cycles.

### 11.1.2 Addition of contamination

The experimental results showed that mixing the polymers with simulated life-cycle factor contaminants such as tape or dirt has shown that processing properties, such as MFI, are usually affected most significantly. Dirt contaminants stiffen the plastic products initially, but cause the material to reduce in strength after a point of saturation. Dirt contamination tends to reduce MFI to a point where processing becomes unfeasible. Some adhesive tapes can reduce MFI, but can also lower the stiffness of the material. Molecular-level testing has shown that typical contaminants do not affect the molecular structure of the polymers.

Observations during the experimentation showed that the major problem with contaminants are that they can be difficult to fully integrate into the material batch and will leave strata in the material, introducing localised weaknesses, which is unacceptable in thin film production. It is therefore logical to conclude that once all measures have been taken to remove the contamination from the recyclate feedstock, the material should be shredded and mixed in the melt-phase. This will distribute contaminants more homogeneously, reducing the probability of strata and thus minimising weaknesses in the material.

### 11.1.3 Predictive modelling.

A novel predictive model has shown that it is possible to anticipate the material properties of a batch of feedstock material before it has been subjected to the expense of the recycling process. This can be done by calculating the resultant polymer crystallinity based on a few physical properties that would be possible to measure in a small-scale factory laboratory.

It can be concluded that the assessment of the condition of plastic feedstocks for recycling can be assisted by a numerical model, rather than using the opinion of recycling experts alone. This could lead to financial savings and expand new markets for recycling operations. The true value of the model in application to a recycling operation would be subject to the model performing satisfactorily in filed trials.

### 11.1.4 Economic modelling.

The economic modelling developed in this investigation was successful in illustrating how changes in plant operation parameters can affect the financial returns from a plastic film recycling business. This model has application as a tool for convincing investors that a plastic film recycling business is a viable concept.

The modelling of the possible economics of a film recycling business have shown that the commercial recycling of plastic film is viable but can be sensitive to a number of key factors including the price paid for the input material and final product, the proximity of the plant to the waste source, the potential yield of the material and the distribution system by which the product is marketed. Of principal interest the so-called yield parameter, which can force a plant to be unprofitable if there is too much unusable material mixed with the feedstock. This factor was also quoted by a number of industrial experts whilst gathering data for the thesis.

### 11.1.5 Recycled products

This investigation has shown that a raft of new packaging products can be developed using recycled material from waste sources in the UK. As previously highlighted some industry sources have indicated that the market for recycled film products (such as agricultural films and damp-proof membranes) is close to saturation [4]. This is not surprising given that the applications for recycled films is apparently limited to a small number of products. The development of new markets, for example the landfill geotextiles shown in Chapter 7 illustrates the fact that there are untapped applications that could further increase the demand for recycled plastic film. The experimental results presented have shown that the geotextile was capable of matching current products manufactured from virgin stock.

It is therefore logical to look for new ways in which to utilise recycled plastic film because this investigation has shown that recyclates from waste sources are a useful resource. Experimental results have proven that although material properties do change with exposure to life-cycle factors, they can be managed, anticipated and improved as required.

## 11.2 Recommendations

### 11.2.1 Future work potential from this investigation

There is a strong element of transferable research present in this investigation. Although the experimentation has concentrated largely on polyethylene materials it is assumed that other plastic film materials, such as PVC or PP, could be treated in a similar fashion. This implies that a predictive model could be derived and implemented to estimate the life-cycle effects on a number of recycled plastic products that have arisen from mixed waste sources. This in turn would require an updated database for the effect of life-cycle factors on a wider range of polymers, which would be provided by further experimentation.

The results from this investigation can be used as evidence to show to plastic film recyclers in order to make a case for working with material from a mixed waste source. Of particular interest would be economic modelling and the quantitative relationships between processing parameters such as MFI and life-cycle factors such as number of heat cycles and dirt contamination. If the industry recyclers can be persuaded that this is a feasible idea, investors would be more likely to commit to a trial.

For the landfill engineering products, future work should concentrate on expanding potential markets, for example drainage and damp-proof media in civil engineering projects. There could be potential applications in lightweight construction materials that utilise the plastic as a filler. Other applications could include sintering the plastic in-situ for specialised road surfaces and temporary repair patches.

Future work on the practicality of plastic film recovery schemes including bring sites, municipal recovery, transfer station design and how bulk density affects these factors is required. As mentioned in Chapters 1 and 9, logistical factors in plastic film recovery can often mean the difference between success and failure from an economic point of view. Studies to continue from this one should focus on best practice to deliver film for recycling in the most cost-effective manner. This would include the examination of storage vessels, collection vehicles and compaction ratios.

Other aspects of film packaging could be explored such as public perception of recycled packaging. This would be an issue which packaging manufacturers would be interested in. Many applications for plastic film involve the film being translucent such that the contents can be examined. It is unlikely that recycled films would be translucent and there is concern that the appearance of the packaged goods would suffer as a result. It would therefore be pertinent to perform market research on the performance of recycled packaging in terms of customer acceptability.

With the development of a predictive model to anticipate the resultant properties of plastic materials after recycling, a logical continuation would be to develop an expert system that interprets the data from the model. This system could to aid recyclers in making choices on whether to accept material and what its applications would be once processed. The system could suggest acceptability limits and inform the recycler on the suitability of a batch of material to the process in mind. This could also be applied to the recyclate collection company or waste broker, who could sell the material to the most appropriate customer, based on the recommendations from the system.

### 11.2.2 Recommendations for future research

Areas of this investigation which could be additionally expanded include further experimentation and implementation of results. The practical work covered herein tested mostly injection moulded parts, for ease of production and to provide more consistent XRD results. It would be worthwhile to perform further testing on film-blown test profiles to compare the behaviour of recycled material that is made into sub-millimetre thickness.

The tensile testing results showed that a number of test results had poor consistency. This lack of consistency was attributed to the inhomogeneity of the samples. Since some material was from mixed feedstocks, it is less likely that it would be consistent in composition. Future work would benefit from larger numbers of test pieces being used per data value in the UTS and maximum elongation results. Tensile results were not of prime importance, so the work was not repeated. More important were processing parameters such as MFI, which were sufficiently consistent.

Only 20 samples were tested with GPC to determine molecular weight and Polydispersity. It would further enhance the understanding of the heat process and define a larger data set if more GPC testing was undertaken. More work could also be done on a wider variety of contaminants such as thermosetting polymers, paper and adhesive labels.

Longer duration exposure trials to effects such as UV radiation and corrosive environments such as landfill leachate would provide data on the durability of the recycled films. This could include artificial ageing over a simulated process of a number of years to test the long-term suitability of the recycled products suggested in this investigation. Such investigations could also include the evaluation of anti-oxidising agents.

The effect of life-cycle factors such as thermal and photo-oxidative ageing should be examined for recycled materials, including the effects of anti-oxidising additives that are added to plastic products to extend life-spans. Although this investigation has shown that there is an amount of available data on the performance of anti-oxidising additives, it would be useful to compare their effectiveness with recycled material that had previously arisen from a mixed waste source or was partially-oxidised prior to mixing.

Other contaminants such as paper labels, residue from Mechanical Biological Treatment (MBT) and thermosetting plastics could be tested as contaminants to the PE films. Future waste streams could contain some or all of these contaminants and their effects would be valuable to quantify.

Although the data presented has provided evidence that recycling plastic film from municipal waste sources is a viable concept, further evidence will be needed to conclusively prove that it can work as a business opportunity. More data on the production of films via film blowing would provide more reliable data. The use of other non-polyethylene films might also be useful should markets arise, for example with polypropylene films.

Proof of whether the predictive model would succeed in an industrial context would be subject to commissioning field trials to evaluate performance. More data is needed to assess the properties of a wider range of plastic film compounds (including non-polyolefin based materials) and their interactions with each other during recycling. A logical continuation of this research would be to produce blown film from a waste source and evaluate its properties in comparison to the predicted properties from the experimentation covered herein. This would act as a baseline for which to properly estimate the accuracy of the model.

Study of a pilot plant for the recycling of plastic film would be an important addition to this research. Such a plant could be commissioned based on the specifications laid out in the investigation of economic modelling. As previously mentioned, the performance of such an operation would be key in convincing investors that the recycling of plastic film from waste sources is a feasible business opportunity.

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# Appendix A – Composition of municipal solid waste

# The Composition of Municipal Solid Waste in Wales

## Executive Summary

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AEA TECHNOLOGY

December 2003

## The Composition of Municipal Solid Waste in Wales

### 1. Aims and Objectives

The Welsh Assembly Government is committed to a more sustainable approach to waste management. Consequently, in 2002 it published a waste strategy "Wise about Waste" for Wales. This sets out proposals for a challenging but realistic programme of change for the next 20 years which will move Wales away from an over reliance on landfill and maximise the use of unavoidable waste as a resource in order to derive the maximum economic, social and environmental benefit to Wales. It also sets targets for both recycling and composting of municipal solid waste. This Strategy will require 40% of municipal solid waste to be either recycled or composted by the year 2010.

As part of the development of the strategy, the Welsh Assembly Government identified the need for data on the composition of municipal waste, and the factors that determine the amounts and the composition. Consequently, they commissioned a programme of work which would:

- provide data on the composition of municipal solid waste (MSW) in Wales;
- develop a protocol/methodology which could be used in future analyses of municipal waste arisings, and for surveying public attitudes to waste recycling and composting.

A preliminary pilot study enabled the protocol to be developed and this was used to determine an initial estimate of the composition of MSW in Wales. However, the Welsh Assembly Government recognised that further analyses would need to be conducted in order to increase overall confidence in both the composition of MSW in Wales and the proportion of these arisings which are suitable for either recycling or composting. Consequently they commissioned phase 2 of the study in order to obtain analysis data for a total of 9 of the 22 local authorities in Wales.

The work required to meet these objectives was conducted between November 2000 and October 2003. The project was funded by the Welsh Assembly Government, and was undertaken by a team led by AEA Technology, supported by M.E.L Research, Waste Research Ltd and WRc.

### 2. What was done

Although there are considerable data from across the UK on the composition of household collected waste and waste brought to household waste recycling centres

(HWRCs), there were very few data on the composition of the other waste streams in MSW. This study has:

- developed a protocol for analysis of each waste stream which is now being used in other studies;
- provided further data on the composition of waste streams such as litter, bulky household waste and street sweepings;
- provided initial data on the composition of commercial and industrial waste which is collected by local authorities;
- developed household questionnaires from which individual households' characteristics could be compared with the composition of waste collected from individual households;
- identified seasonal trends in the composition of the main waste streams comprising municipal waste.

Analyses were conducted in 9 of the 22 local authorities in Wales. These were selected using the following requirements: three authorities in each of the community types (urban, rural and valley) in Wales, the coverage of all waste collection methods used in Wales, and a wide geographical coverage of Wales. The following nine authorities were selected:

- urban authorities – Cardiff, Flintshire and Wrexham.
- rural authorities – Conwy, Monmouthshire and Pembrokeshire.
- valley authorities – Blaenau Gwent, Caerphilly and Torfaen.

Areas within each of these 9 authorities were then selected to identify households which, between them, provided a suitably representative cross section of both the overall Welsh population and the population of the local authority in which they were situated.

Individual analyses of each of the selected household's waste was conducted, and each selected household was sent a questionnaire for the collection of information on factors affecting both waste generation and waste management. Analyses were also conducted on material brought to household waste recycling sites, litter collections, bulky household collections, street sweepings and waste collected from businesses by local authorities. Analyses were conducted in all four seasons. These data were then used to determine the overall composition of MSW in Wales and to identify the arisings of materials which could be targeted for either recycling or composting.

## 3. Composition

The study analysed a total of 174 tonnes of waste from 9 of the 22 local authorities in Wales. Although no analyses were conducted in the remaining 13 authorities, the information presented on the composition of each stream provides all authorities in Wales with sufficient information to enable them to develop their recycling and composting strategy.

Specific findings from the study on the composition of each waste stream include:

- the arisings of dry recyclable materials in household collected waste are comparable to those determined in other studies in England during the past 10 years;
- the arisings of organic (food, kitchen and garden) waste in household collected waste are higher than those determined 10 years ago; a similar trend has been identified in other recent studies on the composition of this waste stream.
- the main components of bulky household waste are white goods and furniture
- the main components of co-collected waste (waste collected by local authorities from commercial and industrial premises) are paper and food and kitchen waste. There are differences in the composition of waste produced by different types of business; for example, the proportion of food and kitchen waste is highest in waste from hotels and restaurants, and the proportion of recyclable paper is highest in waste from offices, As shown in Table A1.

Table A1 Components of types of waste.

| | **Household collected waste** | **Waste brought to Household waste recycling centres** | **Co-collected waste** |
|---|---|---|---|
| Paper and card | 25 | 8 | 41 |
| Plastic | 11 | 3 | 10 |
| Textiles | 2 | 2 | 1 |
| Other combustibles | 8 | 29 | 7 |
| Non combustibles | 3 | 20 | 1 |
| Glass | 7 | 2 | 4 |
| Organics | 36 | 19 | 28 |
| Metal | 5 | 8 | 5 |
| Electrical items | <1 | 7 | 1 |
| Hazardous items | <1 | 1 | 1 |
| Fines | 3 | 1 | 1 |
| **Total** | **100** | **100** | **100** |

The main components of overall MSW are paper and organics (kitchen and garden waste). The overall biodegradable content of municipal solid waste in Wales is 61%, and this will increase to 65% if the arisings of the non-combustible construction and demolition waste are discounted from the definition of MSW, shown in Figure A1.

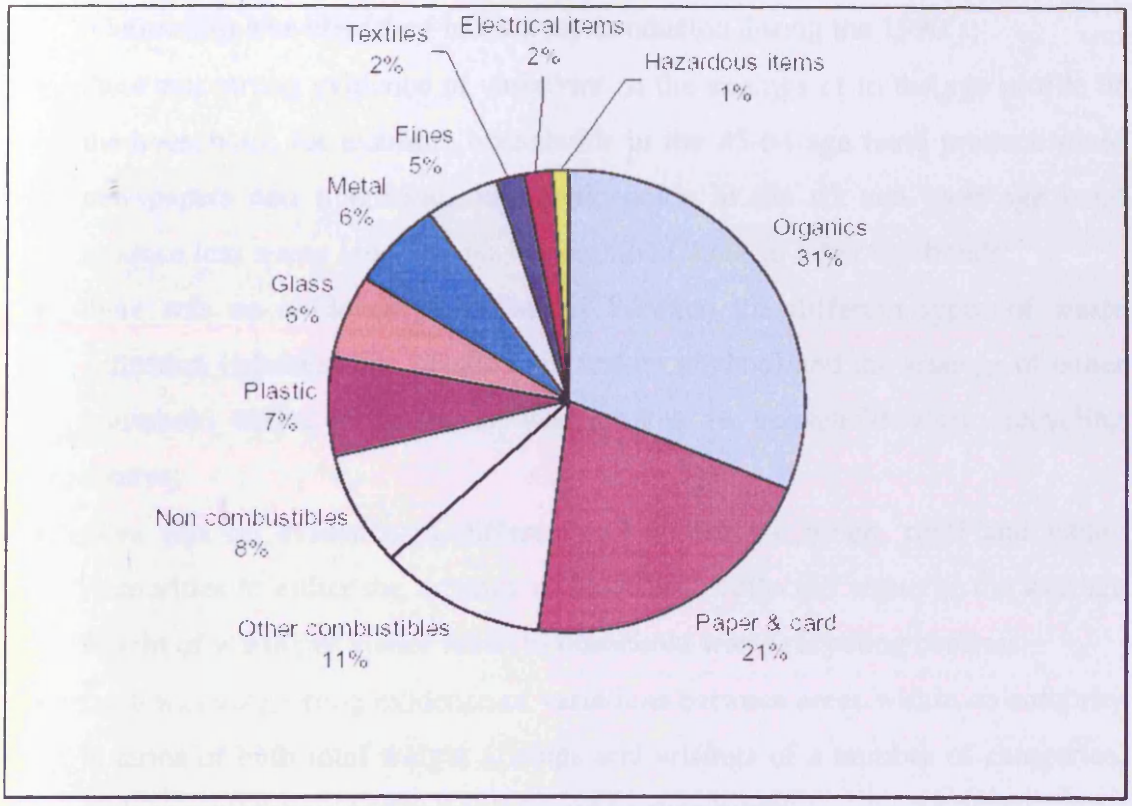


Figure A1 Composition of MSW in Wales

### 4. Factors affecting waste generation

Early models of household waste generation used two main factors to predict waste generation; socio-economic profile and method of collection for household dustbin waste. Later studies identified that there was a relationship between the number of people in the household and the amount of waste produced, and that households in older age groups tended to produce less waste. The current study was designed to assess how factors such as socio-economic factors, type of authority (urban, rural and valley), and method of collection for household dustbin waste affected waste generation.

The main findings from the study on the factors affecting the arisings and composition of individual waste streams were:

- there was a strong seasonal variation in the arisings of garden waste (highest in spring and summer). There was also some evidence for a seasonal variation (highest during Spring and Summer) for plastic bottles;

- there was very strong evidence of a relationship between total weight of waste per household and the number of people living in the household. A similar relationship was identified in a survey conducted during the 1990's;
- there was strong evidence of variations in the arisings of to the age profile of the household; for example households in the 45-64 age band produce more newspapers and magazines, and households in the 65 and over age band produce less waste (and less packaging) than those in other age bands;
- there was no evidence of variations between the different types of waste collection (wheeled bin, plastic sack and no method) and the arisings of either household collected waste or waste taken to household waste recycling centres;
- there was no evidence of differences between the urban, rural and valley Authorities in either the arisings of household collected waste or the average weight of waste per visitor taken to household waste recycling centres;
- there was very strong evidence of variations between areas within an authority in terms of both total weight arisings and arisings of a number of categories, such as newspapers and magazines and kitchen waste.

The results from this study confirm that both the number of people in the household and the age group of the household affect the amount of household collected waste which is produced. However, the study found no statistically significant relationship between the amount of waste generated and either method of collection or the socio-economic profile of the area. This suggests that there is a need to consider whether these factors should be included in future models on waste generation.

## 5. Current recycling

Based on the responses to the household questionnaire, the main findings on current recycling in Wales were that:

- there was some evidence (strongest for glass) that households who used drop-off (bring) recycling schemes more frequently had lower arising of the categories they were placing in their residual waste;
- the main reasons for not recycling were; no collection of recyclables, no convenient bring sites, and no space for storing recyclables;
- the most common method for disposing of organic waste which was not home composted was via the normal household collection.

The questionnaire responses also indicated that only 1% of respondents considered that recycling was not worthwhile.

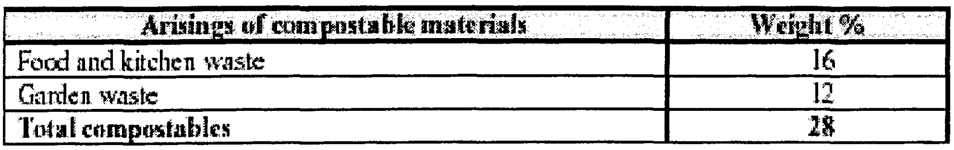
### 6. Potential recycling/composting rate

Tables A2 , A3 and Figure A2 show the composition of households wastes. One of the objectives of the project was to provide information on the arisings of potentially recyclable or compostable materials contained in MSW in Wales. The results obtained indicate that 64% of MSW could potentially be either recycled or composted:

- 36% through recycling; and
- 28% by composting.

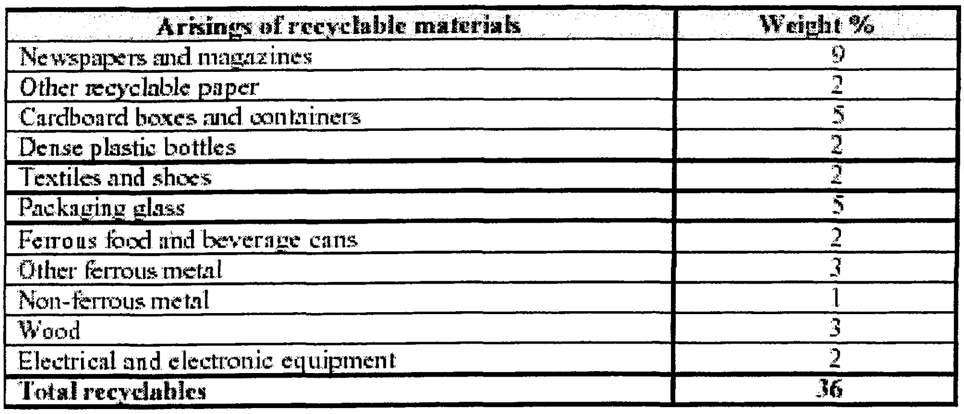
The figure for recycling would increase from 36% to 41% if construction and demolition waste was included.

Table A2 Compostable material arisings



| Arisings of compostable materials | Weight % |
|---|---|
| Food and kitchen waste | 16 |
| Garden waste | 12 |
| **Total compostables** | **28** |

Table A3 Recyclable material arisings



| Arisings of recyclable materials | Weight % |
|---|---|
| Newspapers and magazines | 9 |
| Other recyclable paper | 2 |
| Cardboard boxes and containers | 5 |
| Dense plastic bottles | 2 |
| Textiles and shoes | 2 |
| Packaging glass | 5 |
| Ferrous food and beverage cans | 2 |
| Other ferrous metal | 3 |
| Non-ferrous metal | 1 |
| Wood | 3 |
| Electrical and electronic equipment | 2 |
| **Total recyclables** | **36** |

However, whilst almost two thirds of MSW arisings in Wales could potentially be targeted for recycling or composting, some of these materials are present in streams which local authorities are currently not targeting for recycling. There would be little benefit in, for example, introducing a scheme to collect newspapers and magazines from litter, but local authorities will need to target the co-collected commercial waste stream in order to maximise the potential amounts of cardboard and recyclable paper that they can collect.

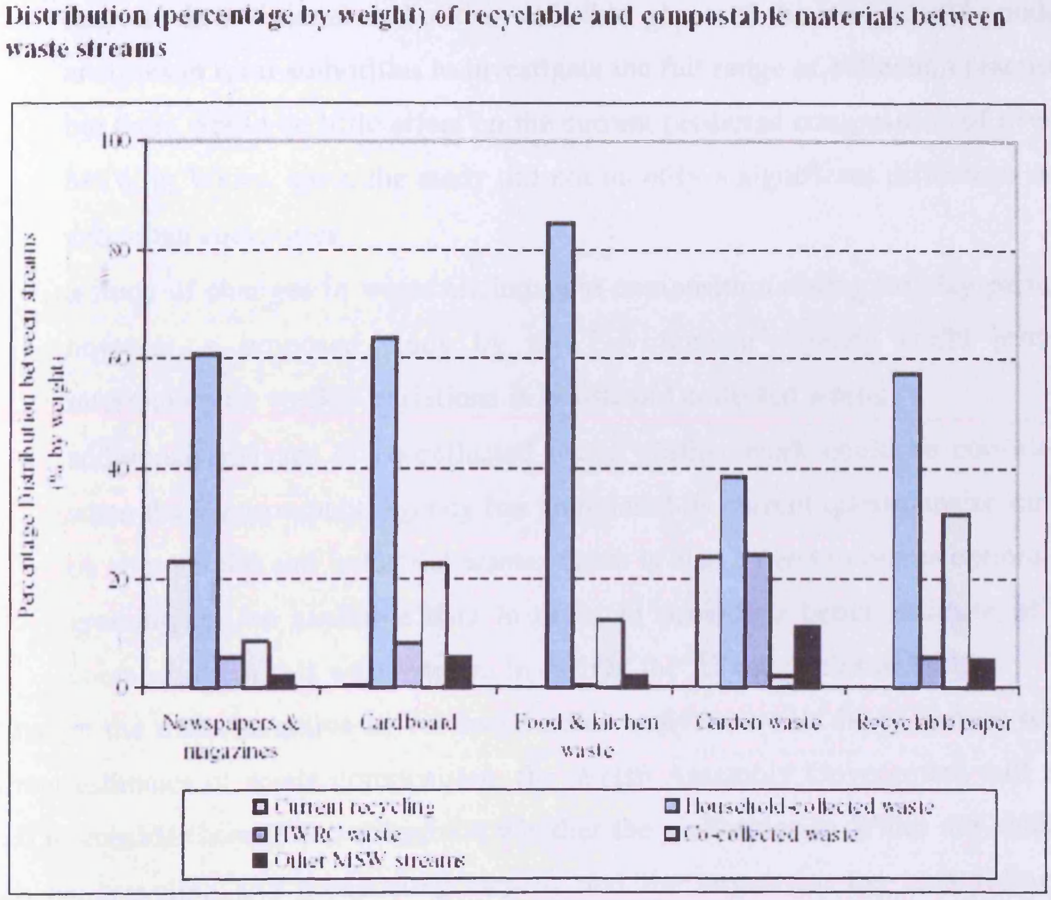

**Distribution (percentage by weight) of recyclable and compostable materials between waste streams**

Figure A2: Distribution of recyclable and Compostable materials.

The recycling rate achieved will be lower than this maximum value for a number of reasons. In areas served by a kerbside collection scheme, a maximum of about 70% of households typically participate in the scheme. When households do participate, they do not always put out all of their recyclable materials for collection. This suggests that even if authorities provide suitable recycling facilities, educate households and businesses on the need to recycle, and secure markets for both the dry recyclables and the compost products, it may be very challenging for them under the current arrangements to meet the 2009/10 targets for recycling and composting set in the Welsh Waste Strategy. Additional methods of increasing participation in recycling and composting schemes may need to be introduced.

## 7. Further work

The study has enabled a considerable amount of data on the arisings and composition of MSW in Wales to be obtained. Possible areas where further work could be considered are:

- analyses in additional authorities; a further phase of the study could conduct analyses in rural authorities to investigate the full range of collection practices, but there would be little effect on the current predicted composition of overall MSW in Wales, since the study did not identify a significant difference rural and urban authorities;
- a study of changes in waste arisings and composition during holiday periods; however, a proposed study by the Environment Agency could provide information on weekly variations in household collected waste;
- additional analyses of co-collected waste; further work could be considered when the Environment Agency has completed its current questionnaire survey on commercial and industrial waste. There is also a need to assess options for grossing up the available data in order to provide a better estimate of the composition of this waste stream in each of the 22 authorities in Wales.

Although the main incentive to conduct further analyses would be to further refine current estimates of waste composition, the Welsh Assembly Government will also need to consider how it can determine whether the authorities in Wales are meeting both the recycling and composting targets, and the targets on the land filling of biodegradable waste set by the Landfill Directive. Further analyses of each waste stream would be useful in 2008-9 to refine landfill diversion targets to meet the more exacting requirements set by the Landfill Directive for 2013 and 2020. This study has shown a significant shift in the composition of household waste since the early 1990s, with significantly more organic waste, and it will be important to track any further significant changes.

# Appendix B – Historic material prices and PRN values data

### Table B1 Plastic film prices: £ per tonne
### October - December 2000

| | October 2000 | November 2000 | December 2000 |
|---|---|---|---|
| **HDPE (high density polyethylene)** | 50 - 120 | 90 - 120 | 90 - 125 |
| **LDPE (low density polethylene)** | 60 - 120 | 60 - 100 | 70 - 100 |

### Table B2 Plastic film prices: £ per tonne
### January - June 2001

| | January 2001 | February 2001 | March 2001 | April 2001 | May 2001 | June 2001 |
|---|---|---|---|---|---|---|
| **HDPE (high density polyethylene)** | 90 – 120 | 90 - 120 | 90 - 140 | 90 - 140 | 100 - 150 | 120 - 170 |
| **LDPE (low density polethylene)** | 70 – 100 | 60 - 100 | 80 - 130 | 80 - 130 | 90 - 140 | 100 - 150 |

### Table B3 Plastic film prices: £ per tonne
### July - December 2001

| | July 2001 | August 2001 | September 2001 | October 2001 | November 2001 | December 2001 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 80 – 160 | 80 - 160 | 80 - 160 | 80 - 160 | 80 - 160 | 80 - 140 |
| **single colour/ natural** | 140 – 250 | 140 - 250 | 140 - 250 | 140 - 240 | 160 - 220 | 150 - 210 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 70 – 150 | 70 - 150 | 70 - 150 | 70 - 150 | 70 - 150 | 70 - 210 |
| **single colour/ natural** | 120 – 240 | 120 - 240 | 120 - 240 | 120 - 230 | 160 - 200 | 140 - 210 |

### Table B4 Plastic film prices: £ per tonne
### January - June 2002

| | January 2002 | February 2002 | March 2002 | April 2002 | May 2002 | June 2002 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 80 – 140 | 80 - 140 | 75 - 135 | 75 - 135 | 75 - 135 | 75 - 135 |
| **single colour/ natural** | 150 - 210 | 150 - 210 | 150 - 205 | 150 - 205 | 150 - 205 | 150 - 205 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 70 - 160 | 70 - 160 | 70 - 155 | 70 - 155 | 70 - 155 | 70 - 155 |
| **single colour/ natural** | 140 - 210 | 140 - 210 | 140 - 205 | 160 - 220 | 160 - 220 | 160 - 220 |

### Table B5 Plastic film prices: £ per tonne
### July - December 2002

| | July 2002 | August 2002 | September 2002 | October 2002 | November 2002 | December 2002 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 75 - 135 | 75 - 135 | 75 - 135 | 75 - 135 | 75 - 130 | 80 – 120 |
| **single colour/ natural** | 150 - 205 | 150 - 205 | 150 - 205 | 150 - 205 | 150 - 200 | 150 – 180 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 70 - 155 | 70 - 155 | 70 - 155 | 70 - 155 | 80 - 150 | 90 - 150 |
| **single colour/ natural** | 140 - 190 | 140 - 190 | 140 - 190 | 140 - 190 | 140 - 190 | 140 – 180 |

### Table B6 Plastic film prices: £ per tonne
### January - June 2003

| | January 2003 | February 2003 | March 2003 | April 2003 | May 2003 | June 2003 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 80 - 100 | 80 - 100 | 80 - 100 | 80 - 100 | 80 - 105 | 80 - 105 |
| **single colour/ natural** | 150 - 180 | 150 - 170 | 150 - 170 | 140 - 160 | 130 - 150 | 130 - 150 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 90 - 140 | 100 - 135 | 100 - 135 | 100 - 140 | 110 - 140 | 110 - 140 |
| **single colour/ natural** | 140 - 170 | 140 - 170 | 140 - 170 | 140 - 170 | 150 - 200 | 150 - 200 |

### Table B7 Plastic film prices: £ per tonne
### July - December 2003

| | July 2003 | August 2003 | September 2003 | October 2003 | November 2003 | December 2003 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 80 - 105 | 80 - 100 | 80 - 100 | 80 - 110 | 80 - 100 | 80 - 100 |
| **single colour/ natural** | 130 - 150 | 125 - 145 | 125 - 145 | 125 - 145 | 110 - 135 | 110 - 135 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 110 - 140 | 100 - 125 | 100 - 125 | 105 - 125 | 100 - 120 | 100 - 120 |
| **single colour/ natural** | 150 - 200 | 150 - 200 | 150 - 200 | 160 - 200 | 160 - 170 | 160 - 190 |

### Table B8 Plastic film prices: £ per tonne
### July - December 2004

| | July 2004 | August 2004 | September 2004 | October 2004 | November 2004 | December 2004 |
|---|---|---|---|---|---|---|
| **HDPE** | | | | | | |
| **mixed colour/ printed** | 100 - 120 | 100 - 130 | 105 - 135 | 105 - 135 | 105 - 140 | 150 - 210 |
| **single colour/ natural** | 150 - 180 | 150 - 180 | 155 - 185 | 155 - 185 | 160 - 200 | 200 - 240 |
| **LDPE** | | | | | | |
| **mixed colour/ printed** | 120 - 160 | 130 - 160 | 135 - 165 | 135 - 165 | 135 - 165 | 180 - 220 |
| **single colour/ natural** | 190 - 210 | 200 - 210 | 205 - 215 | 205 - 215 | 205 - 225 | 230 - 260 |

### Table B9 Plastic bottles prices: £ per tonne
### October - December 2000

| | October 2000 | November 2000 | December 2000 |
|---|---|---|---|
| **Clear and light blue PET** | 120 - 160 | 90 - 140 | 110 - 170 |
| **Coloured PET** | 30 - 60 | 60 - 80 | 60 - 90 |
| **HDPE** | 35 - 150 | 90 - 120 | 90 - 120 |
| **PVC** | 20 - 60 | 20 - 160 | 20 - 60 |
| **Mixed** | 20 - 50 | 30 - 50 | 30 - 50 |

### Table B10 Plastic bottles prices: £ per tonne January - June 2001

| | January 2001 | February 2001 | March 2001 | April 2001 | May 2001 | June 2001 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 110 - 170 | 110 - 170 | 140 - 160 | 140 - 160 | 140 - 160 | 150 – 170 |
| **Coloured PET** | 60 - 90 | 60 - 90 | 60 - 80 | 60 - 80 | 60 - 80 | 70 – 90 |
| **HDPE** | 90 - 120 | 90 - 120 | 100 - 130 | 100 - 130 | 100 - 130 | 115 – 150 |
| **PVC** | 20 - 60 | 20 - 60 | 60 - 70 | 60 - 70 | 60 - 70 | 50 – 70 |
| **Mixed** | 30 - 50 | 30 - 50 | 40 - 70 | 40 - 70 | 40 - 70 | 45 – 80 |

### Table B11 Plastic bottles prices: £ per tonne July - December 2001

| | July 2001 | August 2001 | September 2001 | October 2001 | November 2001 | December 2001 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 150 - 170 | 150 - 170 | 150 - 170 | 150 - 160 | 140 - 150 | 90 – 130 |
| **Coloured PET** | 70 - 90 | 70 - 90 | 70 - 80 | 65 - 75 | 55 - 65 | 0 – 60 |
| **HDPE** | 115 - 150 | 115 - 150 | 140 - 180 | 140 - 165 | 130 - 155 | 100 – 145 |
| **PVC** | 50 - 70 | 50 - 70 | 60 - 80 | 55 - 75 | 45 - 65 | 10 – 20 |
| **Mixed** | 45 - 80 | 45 - 80 | 45 - 80 | 40 - 70 | 30 - 60 | 10 – 40 |

### Table B12 Plastic bottles prices: £ per tonne January - June 2002

| | January 2002 | February 2002 | March 2002 | April 2002 | May 2002 | June 2002 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 90 - 130 | 90 - 130 | 90 - 130 | 90 - 130 | 90 - 130 | 90 – 130 |
| **Coloured PET** | 0 - 50 | 0 - 50 | 0 - 45 | 0 - 45 | 0 - 45 | 0 – 45 |
| **HDPE** | 100 - 140 | 100 - 140 | 100 - 140 | 100 - 140 | 100 - 140 | 100 – 140 |
| **PVC** | 10 - 20 | 10 - 20 | 0 - 20 | 0 - 20 | 10 - 20 | 0 – 20 |
| **Mixed** | 10 - 30 | 10 - 30 | 0 - 30 | 0 - 30 | 10 - 30 | 0 – 30 |

### Table B13 Plastic bottles prices: £ per tonne July - December 2002

| | July 2002 | August 2002 | September 2002 | October 2002 | November 2002 | December 2002 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 90 - 130 | 90 - 130 | 90 - 130 | 90 - 130 | 90 - 120 | 90 – 110 |
| **Coloured PET** | 0 - 45 | 0 - 45 | 0 - 45 | 0 - 45 | 10 - 45 | 30 – 45 |
| **HDPE single col** | 100 - 130 | 100 - 130 | 100 - 130 | 100 - 110 | 90 - 115 | 90 – 110 |
| **HDPE mixed col** | | | | | 75 - 105 | 70 – 110 |
| **PVC** | 0 - 20 | 0 - 20 | 0 - 20 | 0 - 20 | 10 - 20 | 10 – 15 |
| **Mixed** | 0 - 35 | 0 - 35 | 0 - 35 | 0 - 35 | 0 - 35 | 20 - 40 |

### Table B14 Plastic bottles prices: £ per tonne January - June 2003

| | January 2003 | February 2003 | March 2003 | April 2003 | May 2003 | June 2003 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 80 - 100 | 80 - 100 | 80 - 100 | 80 - 90 | 70 - 90 | 70 – 90 |
| **Coloured PET** | 30 - 45 | 30 - 40 | 30 - 40 | 20 - 40 | 10 - 30 | 10 – 30 |
| **HDPE single col** | 85 - 95 | 80 - 90 | 80 - 90 | 80 - 100 | 80 - 100 | 80 – 100 |
| **HDPE mixed col** | 75 - 90 | 60 - 80 | 60 - 80 | 15 - 20 | 18 - 25 | 18 – 25 |
| **PVC** | 5 - 20 | 5 - 15 | 5 - 15 | 40 - 50 | 40 - 50 | 40 – 50 |
| **Mixed** | 10 - 20 | 10 - 20 | 10 - 20 | 15 - 25 | 25 - 40 | 25 - 40 |

### Table B15 Plastic bottles prices: £ per tonne

**July - December 2003**

| | July 2003 | August 2003 | September 2003 | October 2003 | November 2003 | December 2003 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 70 - 90 | 60 - 85 | 60 - 85 | 75 - 95 | 65 - 95 | 65 – 95 |
| **Coloured PET** | 10 - 30 | 15 - 30 | 15 - 30 | 20 - 35 | 20 - 35 | 15 – 45 |
| **HDPE single col** | 80 - 100 | 80 - 100 | 80 - 100 | 90 - 110 | 80 - 105 | 80 – 100 |
| **HDPE mixed col** | 18 - 25 | 60 - 80 | 60 - 80 | 60 - 80 | 60 - 80 | 60 – 75 |
| **PVC** | 40 - 50 | 20 - 30 | 20 - 30 | 15 - 25 | 5 - 25 | 5 – 25 |
| **Mixed** | 25 - 40 | 25 - 40 | 25 - 40 | 25 - 40 | 20 - 40 | 15 – 40 |

### Table B16 Plastic bottles prices: £ per tonne

**July - December 2004**

| | July 2004 | August 2004 | September 2004 | October 2004 | November 2004 | December 2004 |
|---|---|---|---|---|---|---|
| **Clear and light blue PET** | 65 - 85 | 65 - 85 | 60 - 90 | 60 - 90 | 70 - 100 | 80 – 120 |
| **Coloured PET** | 20 - 40 | 25 - 45 | 30 - 50 | 30 - 50 | 35 - 60 | 40 – 65 |
| **HDPE single col** | 65 - 95 | 70 - 95 | 65 - 95 | 65 - 95 | 70 - 100 | 80 – 120 |
| **HDPE mixed col** | 60 - 70 | 60 - 70 | 60 - 70 | 60 - 70 | 60 - 80 | 60 – 90 |
| **PVC** | 15 - 25 | 15 - 25 | 10 - 28 | 10 - 28 | 10 - 25 | 10 – 25 |
| **Mixed** | 0 - 10 | 10 - 20 | 5 - 23 | 5 - 23 | 10 - 30 | 20 - 50 |

### Table B17 £ per PRN/one tonne of material

**October - December 2000**

| | October 2000 | November 2000 | December 2000 |
|---|---|---|---|
| **Glass** | 5 - 9 | 8 - 10 | 8 – 10 |
| **Paper** | 5 - 9 | 8 - 11 | 8 - 11 |
| **Aluminium** | 15 - 20 | 15 - 20 | 15 – 20 |
| **Steel** | 6 - 10 | 8 - 15 | 8 - 15 |
| **Plastics** | 25 - 40 | 35 - 50 | 35 - 50 |
| **Mixed —energy recovery** | 5 - 9 | 4 - 8 | 4 – 8 |
| **Wood — recovery** | 4 - 9 | 4 - 8 | 4 – 8 |

### Table B18 £ per PRN/one tonne of material

**January - June 2001**

| | January 2001 | February 2001 | March 2001 | April 2001 | May 2001 | June 2001 |
|---|---|---|---|---|---|---|
| **Glass** | 12 - 20 | 15 - 22 | 17 - 21 | 17 - 21 | 17 - 22 | 17 – 22 |
| **Paper** | 12 - 16 | 15 - 22 | 15 - 20 | 15 - 20 | 16 - 20 | 16 – 20 |
| **Aluminium** | 20 | 18 - 25 | 18 - 22 | 19 - 21 | 20 - 21 | 20 – 21 |
| **Steel** | 12 - 20 | 15 - 22 | 17 - 20 | 17 - 20 | 18 - 20 | 18 – 20 |
| **Plastics** | 40 - 45 | 45 - 75 | 37 - 45 | 38 - 48 | 40 - 45 | 40 – 45 |
| **Mixed — energy recovery** | 8 - 12 | 10 - 15 | 10 - 15 | 11 - 15 | 12 - 15 | 14 – 15 |
| **Wood — recovery** | 8 - 12 | 10 - 15 | 10 - 15 | 11 - 15 | 13 - 15 | 14 – 15 |

### Table B19 £ per PRN/one tonne of material

**July - December 2001**

| | July 2001 | August 2001 | September 2001 | October 2001 | November 2001 | December 2001 |
|---|---|---|---|---|---|---|
| **Glass** | 19 - 25 | 19 - 25 | 19 - 25 | 20 - 25 | 22 - 28 | 23 – 28 |
| **Paper** | 18 - 22 | 19 - 25 | 19 - 25 | 20 - 25 | 20 - 28 | 20 – 27 |
| **Aluminium** | 20 - 21 | 20 - 21 | 20 - 21 | 20 - 21 | 20 - 25 | 25 - 40 |
| **Steel** | 18 - 22 | 18 - 23 | 18 - 23 | 18 - 23 | 20 - 24 | 20 - 23 |
| **Plastics** | 45 - 50 | 40 - 50 | 45 - 55 | 45 - 55 | 45 - 60 | 20 – 45 |
| **Mixed — energy recovery** | 14 - 16 | 14 - 16 | 14 - 16 | 15 - 17 | 16 - 20 | 16 - 24 |
| **Wood — recovery** | 14 - 16 | 14 - 16 | 14 - 16 | 15 - 17 | 16 - 20 | 16 - 24 |

### Table B20 £ per PRN/one tonne of material
### January - June 2002

| | January 2002 | February 2002 | March 2002 | April 2002 | May 2002 | June 2002 |
|---|---|---|---|---|---|---|
| Glass | 20 - 25 | 25 - 27 | 25 - 27 | 25 - 27 | 23 - 30 | 24 - 31 |
| Paper | 20 - 25 | 25 - 27 | 25 - 28 | 25 - 28 | 25 - 30 | 27 - 31 |
| Aluminium | 26 - 30 | 30 - 35 | 30 - 40 | 30 - 40 | 30 - 40 | 33 - 44 |
| Steel | 20 - 24 | 25 - 30 | 25 - 30 | 25 - 30 | 28 - 32 | 28 - 32 |
| Plastics | 30 - 40 | 38 - 42 | 35 - 45 | 35 - 45 | 30 - 40 | 30 - 39 |
| Mixed — energy recovery | 16 - 20 | 18 - 23 | 22 - 25 | 22 - 25 | 20 - 24 | 21 - 24 |
| Wood — recovery | 16 - 20 | 18 - 23 | 22 - 25 | 22 - 25 | 20 - 24 | 23 - 27 |

### Table B21 £ per PRN/one tonne of material
### July - December 2002

| | July 2002 | August 2002 | September 2002 | October 2002 | November 2002 | December 2002 |
|---|---|---|---|---|---|---|
| Glass | 23 - 30 | 25 - 33 | 27 - 35 | 26 - 35 | 26 - 33 | 16 – 19 |
| Paper | 28 - 32 | 28 - 32 | 28 - 32 | 28 - 31 | 26 - 30 | 15 - 19 |
| Aluminium | 36 - 48 | 36 - 50 | 36 - 50 | 36 - 47 | 32 - 45 | 22 - 30 |
| Steel | 28 - 33 | 28 - 32 | 28 - 33 | 29 - 31 | 24 - 29 | 14 – 18 |
| Plastics | 30 - 38 | 30 - 40 | 30 - 40 | 30 - 40 | 25 - 33 | 19 – 22 |
| Mixed — energy recovery | 22 - 25 | 23 - 30 | 23 - 30 | 25 - 31 | 25 - 30 | 13 - 16 |
| Wood — recovery | 25 - 29 | 25 - 31 | 25 - 31 | 25 - 30 | 23 - 29 | 15 - 19 |

### Table B22 £ per PRN/one tonne of material
### January - June 2003

| | January 2003 | February 2003 | March 2003 | April 2003 | May 2003 | June 2003 |
|---|---|---|---|---|---|---|
| Glass | 15 - 19 | 15 - 19 | 13 - 18 | 10 - 15 | 10 - 12 | 8 - 10 |
| Paper | 12 - 15 | 12 - 15 | 10 - 15 | 9 - 13 | 6 - 11 | 6 - 11 |
| Aluminium | 18 - 22 | 18 - 22 | 18 - 22 | 12 - 16 | 10 - 14 | 10 – 12 |
| Steel | 14 - 16 | 14 - 16 | 13 - 16 | 10 - 15 | 9 - 11 | 7 - 10 |
| Plastics | 10 - 12 | 14 - 18 | 14 - 18 | 9 - 12 | 9 - 11 | 7 – 10 |
| Mixed — energy recovery | 12 - 15 | 12 - 15 | 12 - 15 | 10 - 12 | 8 - 11 | 7 – 10 |
| Wood — recovery | 12 - 15 | 12 - 15 | 12 - 15 | 8 - 12 | 7 - 11 | 7 – 10 |

### Table B23 £ per PRN/one tonne of material
### July - December 2003

| | July 2003 | August 2003 | September 2003 | October 2003 | November 2003 | December 2003 |
|---|---|---|---|---|---|---|
| Glass | 5 - 9 | 6 - 11 | 7 - 11 | 7 - 10 | 7 - 10 | 8 – 11 |
| Paper | 4 - 8 | 3 - 6 | 3 - 6 | 2 - 5 | 2 - 5 | 2 – 5 |
| Aluminium | 10 - 12 | 10 - 12 | 10 - 13 | 10 - 12 | 9 - 12 | 12 – 15 |
| Steel | 6 - 9 | 6 - 9 | 6 - 9 | 4 - 7 | 2 - 5 | 4 – 7 |
| Plastics | 5 - 8 | 5 - 7 | 4 - 7 | 3 - 6 | 3 - 6 | 3 – 6 |
| Mixed — energy recovery | 5 - 8 | 5 - 6 | 4 - 6 | 2 - 6 | 2 - 6 | 3 – 6 |
| Wood — recovery | 5 - 8 | 5 - 7 | 4 - 6 | 2 - 6 | 2 - 6 | 3 – 6 |

**Table B24 £ per PRN/one tonne of material**
**January - June 2003**

| | January 2003 | February 2003 | March 2003 | April 2003 | May 2003 | June 2003 |
|---|---|---|---|---|---|---|
| **Glass** | 15 - 19 | 15 - 19 | 13 - 18 | 10 - 15 | 10 - 12 | 8 - 10 |
| **Paper** | 12 - 15 | 12 - 15 | 10 - 15 | 9 - 13 | 6 - 11 | 6 - 11 |
| **Aluminium** | 18 - 22 | 18 - 22 | 18 - 22 | 12 - 16 | 10 - 14 | 10 – 12 |
| **Steel** | 14 - 16 | 14 - 16 | 13 - 16 | 10 - 15 | 9 - 11 | 7 - 10 |
| **Plastics** | 10 - 12 | 14 - 18 | 14 - 18 | 9 - 12 | 9 - 11 | 7 – 10 |
| **Mixed — energy recovery** | 12 - 15 | 12 - 15 | 12 - 15 | 10 - 12 | 8 - 11 | 7 – 10 |
| **Wood — recovery** | 12 - 15 | 12 - 15 | 12 - 15 | 8 - 12 | 7 - 11 | 7 – 10 |

**Table B25 £ per PRN/one tonne of material**
**July - December 2003**

| | July 2003 | August 2003 | September 2003 | October 2003 | November 2003 | December 2003 |
|---|---|---|---|---|---|---|
| **Glass** | 5 - 9 | 6 - 11 | 7 - 11 | 7 - 10 | 7 - 10 | 8 – 11 |
| **Paper** | 4 - 8 | 3 - 6 | 3 - 6 | 2 - 5 | 2 - 5 | 2 – 5 |
| **Aluminium** | 10 - 12 | 10 - 12 | 10 - 13 | 10 - 12 | 9 - 12 | 12 – 15 |
| **Steel** | 6 - 9 | 6 - 9 | 6 - 9 | 4 - 7 | 2 - 5 | 4 – 7 |
| **Plastics** | 5 - 8 | 5 - 7 | 4 - 7 | 3 - 6 | 3 - 6 | 3 – 6 |
| **Mixed — energy recovery** | 5 - 8 | 5 - 6 | 4 - 6 | 2 - 6 | 2 - 6 | 3 – 6 |
| **Wood — recovery** | 5 - 8 | 5 - 7 | 4 - 6 | 2 - 6 | 2 - 6 | 3 – 6 |

**Table B26 £ per PRN/one tonne of material**
**January - June 2004**

| | January 2004 | February 2004 | March 2004 | April 2004 | May 2004 | June 2004 |
|---|---|---|---|---|---|---|
| **Glass** | 17 - 23 | 18 - 23 | 18 - 23 | 18 - 22 | 20 - 24 | 23 - 27 |
| **Paper** | 7 - 9 | 7 - 9 | 8 - 9 | 7 - 9 | 8 - 10 | 9 - 10 |
| **Aluminium** | 20 - 25 | 21 - 26 | 21 - 26 | 20 - 25 | 21 - 26 | 21 - 26 |
| **Steel** | 10 - 15 | 10 - 15 | 11 - 15 | 11 - 15 | 11 - 15 | 12 - 16 |
| **Plastics** | 6 - 9 | 6 - 9 | 6 - 9 | 7 - 9 | 8 - 10 | 8 - 10 |
| **Mixed — energy recovery** | 4 - 7 | 4 - 7 | 4 - 7 | 2 - 5 | 2 - 4 | 2 - 4 |
| **Wood** | 4 – 7 | 6 - 8 | 6 - 8 | 6 - 8 | 7 - 9 | 8 - 10 |

**Table B27 £ per PRN/one tonne of material**
**July - December 2004**

| | July 2004 | August 2004 | September 2004 | October 2004 | November 2004 | 1 December 2004 | 15 December 2004 |
|---|---|---|---|---|---|---|---|
| **Glass** | 22 - 27 | 20 – 25 | 16 - 18 | 15 - 18 | 13 - 16 | 7 - 10 | 7 - 10 |
| **Paper** | 9 - 10 | 8 – 10 | 7 - 9 | 5 - 7 | 5 - 7 | 7 - 10 | 7 - 10 |
| **Aluminium** | 23 - 28 | 24 – 29 | 22 – 25 | 22 - 25 | 22 - 25 | 33 - 36 | 33 – 36 |
| **Steel** | 14 - 16 | 15 – 17 | 16 - 18 | 16 - 18 | 16 - 18 | 33 - 36 | 33 - 36 |
| **Plastics** | 8 - 10 | 9 – 11 | 11 – 13 | 15 - 17 | 22 - 25 | 30 - 40 | 30 - 40 |
| **Mixed — energy recovery** | 2 - 4 | 2 – 3 | 1 - 2 | 1 - 2 | 1 - 2 | 1 - 2 | 1 - 2 |
| **Wood** | 8 - 10 | 8 – 10 | 6 - 8 | 5 - 7 | 5 - 7 | 6 - 9 | 6 - 9 |

# Appendix C – Companies engaged in the recycling of plastic film

Table C1 Name and location of recycling companies

| **Company Name** | **Location** |
|---|---|
| Acedag Ltd | RUGELEY |
| ACP Plastics Ltd | HEREFORD |
| Addcolour Plastics Ltd | WIGAN |
| A & D Polymers | ILKESTON, Derbyshire |
| Alpha Polymers Ltd | LIVERPOOL |
| A T Recycling | WOLVERHAMPTON |
| Axis Packaging | LIVERPOOL |
| Birmingham Plastic Recycling | Smethwick, West Midlands |
| Borders Recycling Company and Associates | Hexham, Northumberland |
| **Alida Recycling,** | **HEANOR, Derbyshire** |
| **Anaplast (Greenock),** | **GREENOCK** |
| **Visqueen Building Products** | **RHYMNEY** |
| **Dumfries Plastics Recycling,** | **DUMFRIES** |
| **Hygiene Products Ltd,** | **ILKESTON** |
| **bpi.recycled products (formerly PCL Recycling),** | **STROUD** |
| Zedcor | WITNEY, Oxfordshire |
| Britton Merlin Ltd | LOUTH |
| Britton Taco Ltd | WINSFORD, Cheshire |
| Caledonian Industries Ltd | GLASGOW |
| Centriforce Plastics Ltd (formerly Chisholm Plastics) | LIVERPOOL |
| Chase Plastics Ltd | BRANDON |
| Chase Plastics Ltd | Glasshoughton |
| Cogran Reclamation Ltd | Bold, ST HELENS |
| Combat Polystyrene Group Ltd | GLOSSOP, Derbyshire |
| James W Corry & Sons (Campsie) Ltd | LONDONDERRY |
| Corpak | GLOSSOP, Derbyshire |
| Crosby Reclaimed Plastics | LIVERPOOL |
| Damplas | COVENTRY |
| Delleve Plastics Ltd | STRATFORD-ON-AVON, Warwickshire |
| Denroyd Ltd | HALIFAX |
| Dolphin Packaging Materials Ltd | CHRISTCHURCH, Dorset |
| Elite Plastics Ltd | HEREFORD |
| Extrusion & Moulding Compounds Ltd | Pontypool, Gwent |
| Fewsters Ltd | SUNDERLAND, Tyne & Wear |
| Flo-Pak (UK) Ltd | BRACKLEY, Northants |
| Gelpack Excelsior Limited | HEREFORD |
| Gelpack Industrial Ltd | HEREFORD |
| G & H Plastics Ltd | HALIFAX, West Yorkshire |
| Industrial Plastics Recycling Ltd | Knighton, Powys |
| James Heys & Sons Ltd | Canvey Island, Essex |
| JJ Plastics | Manchester |
| JJ Plastics | Flint, Flintshire |
| JKN Polymers Ltd | BEVERLEY, Yorkshire |
| Kay-Metzeler | BASILDON, Essex |
| Derek Lambert Polythene Ltd | Bingley, West Yorkshire |
| LBS Thermoform Ltd | COLNE, Lancashire |
| Linpac Plastics Ltd | CASTLEFORD, West Yorkshire |
| LMMA Recycling | ERITH, Kent |
| Mainetti (UK) Ltd | DEESIDE, Flintshire |

Table C1 Name and location of recycling companies (continued)

| **Company Name** | **Location** |
|---|---|
| Marchant Manufacturing Co Ltd | HAVERHILL, Suffolk |
| Frank Mercer & Sons Ltd | Westhoughton, BOLTON |
| Mole Plastics Ltd | CIRENCESTER, Gloucestershire |
| Next Century Recycling Ltd | SWINDON,Wiltshire |
| Norfrost Ltd | CASTLETOWN, Caithness |
| Norpol Recycling Ltd | NELSON, Lancashire |
| Paperwaste (Notts) Ltd | RETFORD, Nottinghamshire |
| B & J Parr | MANSFIELD WOODHOUSE, Nottinghamshire |
| Petlon Polymers Ltd | LYDNEY, Gloucestershire |
| Plastic Recycling Centre Ltd | Radcliffe, MANCHESTER |
| Plastic Technology Services Ltd | Dumfries |
| PLYSU Recycling, | Kempston, BEDFORD |
| Plysu Liquid Foods Ltd | Yate, BRISTOL |
| Plysu Liquid Foods Ltd | NEWPORT PAGNELL, Buckinghamshire |
| Plysu Liquid Foods Ltd | ROCHDALE, Lancashire |
| Preston Plastics Ltd | Out Rawcliffe, PRESTON |
| Precision Polymers Reclaims (Stroud) Ltd | STROUD, Gloucestershire |
| Remarkable (Pencils) Ltd | London |
| Reprise Ltd | Bold, ST HELENS |
| Re-Tex Plastic Technology Limited | SKELMERSDALE, Lancashire |
| Roydon Granulation Ltd | Baxters Lane, ST HELENS |
| Roydon Polythene | ROCHDALE |
| Scanturn Ltd | RUGELEY, Staffordshire |
| Scottish Recycling | ABERDEEN |
| Selucid Ltd | Walkden, MANCHESTER |
| Smith Anderson & Company Ltd | Falkland, FIFE |
| S S Thermoplastics | Halmerend, STOKE-ON-TRENT |
| Styrene Packaging & Insulation Ltd | Low Moor, BRADFORD |
| Synbra Polymers Ltd | Eaton, CONGLETON |
| Technopolymers Ltd | BRIDGEWATER, Somerset |
| Tripenta Ltd | BROADWAY, Worcestershire |
| Vencel Resil Ltd | BELVEDERE, Kent |
| Vencel Resil Ltd | Parkhead, GLASGOW |
| Vencel Resil Ltd | LYDNEY, Gloucestershire |
| Waste Exchange Services Limited | STOCKTON-ON-TEES |
| West Midland Recycling Ltd | BIRMINGHAM |
| J & A Young (Leicester) Ltd | LOUGHBOROUGH |

# Appendix D – EN643 paper recycling specifications

**European Standard Grades**

This list of European standard grades of recovered paper and board gives a general description of the standard grades by defining what they do and do not contain.

The list is for use by industry professionals, organisations and individuals with an interest in the recovered paper sector to assist in the buying and selling of this raw material intended for recycling by the paper and board industry.

The list also provides help and support for Customs and Excise Officers who are required to classify these raw materials from waste in the context of supranational legislation on the control of waste movement.

It is not the purpose to specify all the qualities of recovered paper and board that exist in the different markets, but rather to define those qualities most commonly traded in Europe. The description of the grades is brief, and for this reason it is recognised that specific deals between buyer and supplier for grades with special specifications will still be necessary to meet individual requirements and will not be excluded by any implied regulations associated with the publication of this list.

Paper and board mills may ask for a declaration from the supplier about the origin of the material, in relation to national regulations or standard requirements.

Recovered paper from refuse sorting stations is not suitable for use in the paper industry.

Recovered paper and board originating from multi material collection systems, containing only material of a valuable, recyclable nature, has to be specifically marked. It is not permissible to mix it unmarked with other recovered paper and board.

The list contains a group of recovered paper grades (Group 5 "Special Grades") that, in most cases, can only be recycled using specific processes, or can cause some particular constraints to recycling. Their inclusion in the list is justified by the existence of a significant European market. Actual recycling of the specific qualities can only be done by a limited number of mills located in a few countries only.

Definitions

Unusable materials

Materials which are unusable in the production of paper and board consist of "non-paper components", and "paper and board detrimental to production". Recovered paper and board should in principle be supplied free of unusable materials, but where for specific grades a certain proportion of unusable materials is agreed between purchaser and supplier, it shall refer solely to the element described as "paper and board detrimental to production".

Non-paper components

These consist of any foreign matter in the recovered paper and board which, during processing, may cause damage to machines or interruptions to production or may reduce the value of the finished product, such as:

metal
plastic
glass
textiles
wood
sand and building materials
synthetic materials
"synthetic papers"

Paper and board detrimental to production

These are grades of paper and board which have been recovered or treated in such a way that they are, for a basic or standard level of equipment, unsuitable as raw material for the manufacture of paper and board, or are actually damaging, or whose presence makes the whole consignment of paper unusable.

A growing number of mills have, however, adapted treatment plants to handle such grades and the range of papers and boards capable of being recycled is increasing all the time as technology develops. The criteria for defining the percentage of "unusable materials" for these grades will be subject to individual mills' specifications.

Moisture content

Recovered paper and board will, in principle, be supplied with moisture of not more than the naturally occurring level. Where the moisture content is higher than 10% (of air dried weight), the additional weight in excess of 10% may be claimed back – with the method of testing and sampling to be agreed between buyer and seller.

To the numbering system

Recovered paper grades have been numbered in this list according to a numerical code system as follows:

**x.yy.ww**

where:

x: group

y: grade

w: subgrade

**Group 1 - Ordinary Grades**

**1.01 - Mixed paper and board, unsorted, but unusable materials removed**

A mixture of various grades of paper and board, without restriction on short fibre content.

**1.02 - Mixed papers and board (sorted)**

A mixture of various qualities of paper and board, containing a maximum of 40% of newspapers and magazines.

**1.03 - Grey board**

Printed and unprinted white lined and unlined grey board or mixed board, free from corrugated material.

**1.04 - Supermarket corrugated paper and board.**

Used paper and board packaging, containing a minimum of 70% of corrugated board, the rest being solid board and wrapping papers.

**1.05 - Old corrugated containers**

Used boxes and sheets of corrugated board of various qualities.

**1.06 - Unsold magazines**

Unsold magazines, with or without glue.

**1.06.01 - Unsold magazines without glue**

Unsold magazines without glue.

**1.07 - Telephone Books**

New and used telephone books, with unlimited content of pages coloured in the mass, with and without glue. Shavings allowed.

**1.08 - Mixed newspapers and magazines I**

A mixture of newspapers and magazines, containing a minimum of 50% of newspapers, with or without glue.

**1.09 - Mixed newspapers and magazines II**

A mixture of newspapers and magazines, containing a minimum of 60% of newspapers, with or without glue.

**1.10 - Mixed magazines and newspapers**

A mixture of newspapers and magazines, containing a minimum of 60% of magazines, with or without glue.

**1. 11- Sorted graphic paper for deinking**

Sorted graphic paper from households, newspapers and magazines, each at a minimum of 40%. The percentage of non-deinkable paper and board should be reduced over time to a maximum level of 1.5%. The actual percentage is to be negotiated between buyer and seller.

**Group 2 - Medium Grades**

**2.01 - Newspapers**

Newspapers, containing a maximum of 5% of newspapers or advertisements coloured in the mass.

**2.02 - Unsold newspapers**

Unsold daily newspapers, free from additional inserts or illustrated material coloured in the mass.

**2.02.01- Unsold newspapers, no flexographic printing allowed**

Unsold daily newspapers, free from additional inserts or illustrated material coloured in the mass, strings allowed. No flexographic printed material allowed.

**2.03 - Lightly printed white shavings**

Lightly printed white shavings, mainly mechanical pulp based paper.

**2.03.01- Lightly printed white shavings without glue**

Lightly printed white shavings, mainly mechanical pulp based paper, without glue.

**2.04 - Heavily printed white shavings**

Heavily printed white shavings, mainly mechanical pulp based paper.

**2.04.01- Heavily printed white shavings without glue**

Heavily printed white shavings, mainly mechanical pulp based paper, without glue.

**2.05 - Sorted office paper**

Sorted office paper.

**2.06 - Coloured letters**

Correspondence, in mixed papers coloured in the mass, with or without print, of printing or writing paper. Free from carbon paper and hard covers.

**2.07 - White woodfree books**

Books, including misprints of books, without hard covers, mainly of woodfree white paper, black printed only. Containing a maximum of 10% of coated paper.

**2.08 - Coloured woodfree magazines**

Coated or uncoated magazines, white or coloured in the mass, free from non-flexible covers, bindings, non-dispersible inks and adhesives, poster papers, labels or label trim. May include heavily printed circulars and coloured in the mass shavings. Containing a maximum of 10% mechanical pulp based papers.

**2.09 - Carbonless copy paper**

Carbonless copy paper.

**2.10 - Bleached woodfree PE-coated board**

Bleached woodfree PE-coated board from board manufacturers and converters.

**2.11 - Other PE-coated board**

Other PE-coated board. May contain unbleached board and paper from board manufacturers and converters.

**2.12 - Mechanical pulp based computer print-out**

Continuous computer print-out, mechanical pulp based, sorted by colours, may include recycled fibres.

### Group 3 - High Grades

**3.01 - Mixed lightly coloured printers shavings**

Mixed shavings of printing and writing papers, lightly coloured in the mass, containing a minimum of 50% of woodfree paper.

**3.02 - Mixed lightly coloured woodfree printer shavings**

Mixed shavings of printing and writing papers lightly coloured in the mass, containing a minimum of 90% of woodfree paper.

**3.03 - Woodfree binders**

White woodfree lightly printed shavings with glue, free from paper coloured in the mass. May contain a maximum of 10% of mechanical pulp based paper.

**3.04 - Tear white shavings**

White woodfree lightly printed shavings without glue, free from wet-strength paper and paper coloured in the mass.

**3.05 - White woodfree letters**

Sorted white woodfree writing papers, originating from office records, free from cash books, carbon paper and non-water soluble adhesives.

**3.06 - White business forms**

White woodfree printed business forms.

**3.07 - White woodfree computer print-out**

White woodfree computer print-out, free from carbonless paper and glue.

**3.08 - Printed bleached sulphate board**

Heavily printed sheets of bleached sulphate board, without glue, polycoated or waxed materials.

**3.09 - Lightly printed bleached sulphate board**

Lightly printed sheets of bleached sulphate board, without glue, polycoated or waxed materials.

**3.10 - Multi printing**

Woodfree, coated, lightly printed, free from wetstrength paper or paper coloured in the mass.

**3.11 - White heavily printed multiply board**

New cuttings of heavily printed white multi-ply board, containing woodfree, mechanical or thermo-mechanical pulp plies, but without grey plies.

**3.12 - White lightly printed multiply board**

New cuttings of lightly printed white multi-ply board, containing woodfree, mechanical or thermo-mechanical pulp plies, but without grey plies.

**3.13 - White unprinted multiply board**

New cuttings of unprinted white multi-ply board, containing woodfree, mechanical or thermo-mechanical pulp plies, but without grey plies.

**3.14 - White newsprint**

Shavings and sheets of white unprinted newsprint, free from magazine paper.

**3.15 - White mechanical pulp based coated and uncoated paper**

Shavings and sheets of white unprinted coated and uncoated mechanical pulp based paper.

**3.15.01 - White mechanical pulp based paper containing coated paper**

Shavings and sheets of white unprinted mechanical pulp based coated paper.

**3.16 - White woodfree coated paper, without glue**

Shavings and sheets of white unprinted woodfree coated paper, without glue.

**3.17 - White shavings**

Shavings and sheets of white unprinted paper, free from newsprint and magazine paper containing a minimum of 60% of woodfree paper; may contain a maximum of 10% of coated paper. Without glue.

**3.18 - White woodfree shavings**

Shavings and sheets of white unprinted woodfree paper; may contain a maximum of 5% of coated paper. Without glue.

**3.18.01 - White woodfree uncoated shavings**

Shavings and sheets of white unprinted woodfree paper, free from coated paper. Without glue.

**3.19 - Unprinted bleached sulphate board**

Unprinted sheets of bleached sulphate board, without glue, polycoated or waxed materials.

**Group 4 - Kraft Grades**

**4.01 - New shavings of corrugated board**

Shavings of corrugated board, with liners of kraft or testliner

**4.01.01- Unused corrugated kraft**

Unused boxes, sheets and shavings of corrugated board, with kraft liners only, the fluting made from chemical or thermo-chemical pulp.

**4.01.02- Unused corrugating material**

Unused boxes, sheets and shavings of corrugated board, with liners of kraft or testliner.

**4.02 - Used corrugated kraft I**

Used boxes of corrugated board, with kraft liners only, the fluting made from chemical or thermo-chemical pulp.

**4.03 - Used corrugated kraft II**

Used boxes of corrugated board, with liners of kraft or testliners but having at least one liner made of kraft

**4.04 - Used kraft sacks**

Clean used kraft sacks. Wet-strength and non wet-strength.

**4.04.01- Used kraft sacks with polycoated papers**

Clean used kraft sacks. Wet-strength and non wet-strength. May include polycoated papers.

**4.05 - Unused kraft sacks**

Unused kraft sacks. Wet-strength and non wet-strength.

**4.05.01- Unused kraft sacks with polycoated papers**

Unused kraft sacks. Wet-strength and non wet-strength, may include polycoated papers.

**4.06 - Used kraft**

Used kraft paper and board of a natural or white shade.

**4.07 - New kraft**

Shavings and other new kraft paper and board of a natural shade.

### 4.08 - New carrier kraft

New carrier kraft, may include wet-strength paper.

## Group 5 - Special Grades

### 5.01 - Mixed recovered paper and board

Unsorted paper and board, separated at source.

### 5.02 - Mixed packaging

A mixture of various qualities of used paper and board packaging, free from newspapers and magazines.

### 5.03 - Liquid board packaging

Used liquid packaging board including used PE-coated liquid packaging board (with or without aluminium content), containing a minimum of 50% by weight of fibres, and the balance being aluminium or coatings.

### 5.04 - Wrapper kraft

Poly-lined, sprayed, or laminated used kraft. Must not contain bitumen or wax coatings.

### 5.05 - Wet labels

Used wet labels from wet-strength papers, containing a maximum of 1% glass content, and a maximum of 50% moisture, without other unusable materials.

### 5.06 - Unprinted white wet-strength woodfree papers

Unprinted white wet-strength woodfree papers.

### 5.07 - Printed white wet-strength woodfree papers

Printed white wet-strength woodfree papers.

# Appendix E – PAS 103 plastic film specifications

## PAS 103 Plastics Classifier

Table E1 - Waste plastics packaging deliveries - Visual inspection log sheet

**Enter information in drop down boxes and green cells only**

| | | | |
|---|---|---|---|
| Part 1 | | | |
| **Source** | | **Inspection date:** | |
| **Batch ID:** | | **Assessor:** | |
| Net weight of batch, kg Excluding its packaging, e.g. pallets | | | |
| Form of batch | Other (specify) ▼ | | |
| Number of units, e.g. bales or bags, in the batch | | | |
| Where applicable how is the batch packaged? | Plastic strapping ▼ | | |
| Form of waste plastics | Shredded ▼ | | |
| Has the waste been used? | Post consumer ▼ | | |
| Weight of bale or bag, kg | | | |
| Dimensions of bale or bag, m | | | |
| Density of bale or bag, kg/m3 | | | |
| Is the packaging obligated? | Yes ▼ | | |

| | | | |
|---|---|---|---|
| Part 2 | | | |
| **Specification category** | Column 1<br>**Classification and description** | Column 2<br>**Estimate % by weight** [a) c)] | Column 3<br>**Grading (see Tabl 2 & 3)** |
| **1. Main original or originally intended application** [a]**:** (Table 4) | A1, Any pre-use applications, unfilled, without caps and labels (> 1 ▼ | 99.5 | C |
| **2a. Main polymer present** [a]**:** (Table 5) | PET ▼ | 99.0 | D |
| **2b. Other polymer(s) present** [a]**:** (Table 5) | PVC-P ▼ | 1.0 | |
| **3. Main colour** [a) b)]**:** (Table 6) | P2, natural with tint ▼ | 98.0 | E |
| **4. Category A contaminants (hazardous/clinical waste)** [d]**:** (See 4.4.2) | | 0.0 | 1 |
| **5. Category B contaminants** [d]**:** (See 4.4.3) | | 2.0 | 5 |
| **6. Category C contaminants** [d]**:** (See 4.4.4) | | 3.0 | 6 |
| **7. Surface water content:** | dry (no visible water) ▼ | | |

## Table E2
### Classification Decoder

**To use the decoder, enter the classification details in Part 3 below. Full descriptions are then shown in Part 2 below.**

Part 3

| **Full classification and grading** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Application | | Material | | Colour | | Contaminant A | | Contaminant B | | Contaminant C | |
| A9 ▼ | A | PP ▼ | B | P3, single colour ▼ | C | CA | 1 | CB | 4 | CC | 5 |

Part 2

| **Specification category** | Column 1<br>**Classification and description** | Column 2<br>**% by weight** | Column 3<br>**Grading** |
|---|---|---|---|
| **1. Main original or originally intended application**[a]**:** (Table 4) | A9, Any post-use applications, no caps (> 100 ml and < 5 l) | =99.9 % | A |
| **2a. Main polymer present**[a]**:** (Table 5) | PP | =99.8 % | B |
| **2b. Other polymer(s) present**[a]**:** (Table 5) | | | |
| **3. Main colour**[a][b]**:** (Table 6) | P3, single colour | =99.5 % | C |
| **4. Category A contaminants (hazardous/clinical waste)**[d]**:** (See 4.4.2) | | =0.1 % | 1 |
| **5. Category B contaminants**[d]**:** (See 4.4.3) | | =1 % | 4 |
| **6. Category C contaminants**[d]**:** (See 4.4.4) | | =2 % | 5 |

# Appendix F – Erema recycling process

From "Plastic film recycling: production of high quality products from low quality feedstocks" Profit from waste VII seminar 27/10/2004.

# Plastic Film Recycling: Production of High-Quality Products from Low-Quality Feedstocks.

By Richard Marsh, Tony Griffiths, Keith Williams, Sam Evans. Cardiff School of Engineering.

## SYNOPSIS

Plastic film recycling in the United Kingdom is currently only undertaken using film that has come from clean industrial and commercial sources. More heavily contaminated feedstocks, principally those from municipal sources are generally not recycled into new film products because of economic and contamination problems. This paper outlines a cost-effective procedure that can effectively recycle polyethylene film diverted from municipal waste sources.

## 1. INTRODUCTION

The work presented in this paper is the technical aspect of a feasibility study to determine whether it was possible to recycle low-quality waste plastic film from a technical, economic and logistical viewpoint. The paper focuses on the actual recycling process, which is heavily dependent on the recycler's ability to remove contamination from the feedstock. To evaluate the viability of such an operation, a series of recycling plants across Europe were visited and used to process the waste film, which was recovered from a municipal Material Recovery Facility (MRF) in North Wales. Each particular field of recycling expertise at each plant was employed to build a stepwise process to recycle the film from waste recovery to final film extrusion.

### 1.1 Plastic Film Arisings in the UK.

The amount of plastic sheet in the UK domestic waste stream is about 4% by mass, [1]. Municipal waste production is currently of the order of 30 million tonnes per annum, thus it can be assumed that municipal sources produce around 1.2 million tonnes of plastic film per year. Trends in the usage of plastics in packing imply that this figure will increase, coupled with increases in production of MSW. Only a small proportion of this film is currently worth recovering for the purpose of recycling. Estimated amounts of plastic film in the Commercial and Industrial sectors are of the order of 1 million tones per annum [2]. Therefore in total the UK produces an average of around 2.5 million tonnes of plastic film per annum. Of this it is understood that only 200,000 tonnes is recycled [2].

### 1.2 Economics

Previous work by the authors has shown that the economics of film recycling are often cited by industry as the main reason for not working with municipal or contaminated waste sources [3]. Traditionally it has been accepted that the difficulty in operating a washing plant outweighs the economic returns from the sale of the cleaned product it produces. Economic feasibility studies have shown that with more modern washing technology for contamination removal, as outlined in this paper, it is entirely possible to run an economically viable film recycling plant [3].

### 1.3 Steps in the Recycling Process

There were four major steps to the recycling process in this work. Firstly, the waste plastic film was procured and baled at a waste transfer station in North Wales. No attempt was made to separate or purify the material by hand at this point. Secondly the material was shipped to the Ecoplast facility in Italy where it was cleaned in water via a two-stage washing process. Thirdly the material was pelletised at the Erema facility, located in Austria. This process was employed to melt filter the material, i.e. to clean the plastic further by removal of contamination in the liquid state, and to agglomerate the material into pellets for ease of transportation and further manufacture. Fourthly the material was extruded and blown into a number of products, the thinnest having a film thickness of 250 micron.

### 1.4 Modern Film Recycling Practices

Much of the activities in modern plastic film recycling are based on recovery of scrap or off-cut material at manufacturing sites. This is undertaken so that value can be gleaned from manufacturing scrap, rather than wasting what is essentially usable material. The recycling market for back-of-store packaging film, material which has not yet passed into the consumer domain is steadily growing, but film recycling from post-consumer sources is virtually non-existent. There are businesses in operation that are prepared to recycle commercially derived film products, but many of them export the material overseas to be sorted and cleaned in labour-intensive operations where human resource costs are low. Many of these film products are converted into low-value applications such as plastic planks or poor-quality injection moulded parts.

### 1.5 Technology Based Sorting and Cleaning

The integrated process presented in this paper is a fully-automatic manufacturing system that takes waste plastic film, cleans it to an acceptable standard and produces a new film product. Other processes do exist but they are either concerned with recycling clean feedstocks or turning contaminated feedstocks into low-value products. The complete route has not previously been applied to a waste source of such high contamination. Many of the steps used are more commonly associated with processing cleaner material but integrating all of the steps into a single process would simply be a matter of bringing the technologies together.

## 2. The Process

The process to recycle the plastic film from waste to new product was divided into four steps. Each of these steps was carried out in a separate location where the expertise of a particular business was used. It is assumed that were the new process put into commercial operation, most or all of these steps would be carried out at the same site to minimise haulage.

### 2.1. Material Sourcing

Approximately two tonnes of waste plastic film material were supplied by Biffa Ltd from a transfer station associated with a landfill operation in North Wales. This film was then compacted and baled for transportation. The composition of this material appeared to be mostly clear shrink wrapping, along with varieties of blue and black plastic sheet. It was evident that there were significant quantities of paper and cardboard materials mixed in with the plastic feedstock and at this stage no attempt was made to separate the plastic film from the contaminants. Other smaller contaminants included wire, plastic strapping and fragments of wood. Figure F1 shows the film being unloaded at the washing plant in Southern Italy. A schematic of the plant in shown in Figure F2.

Figure F1 Unsorted plastic film being unloaded from bales.

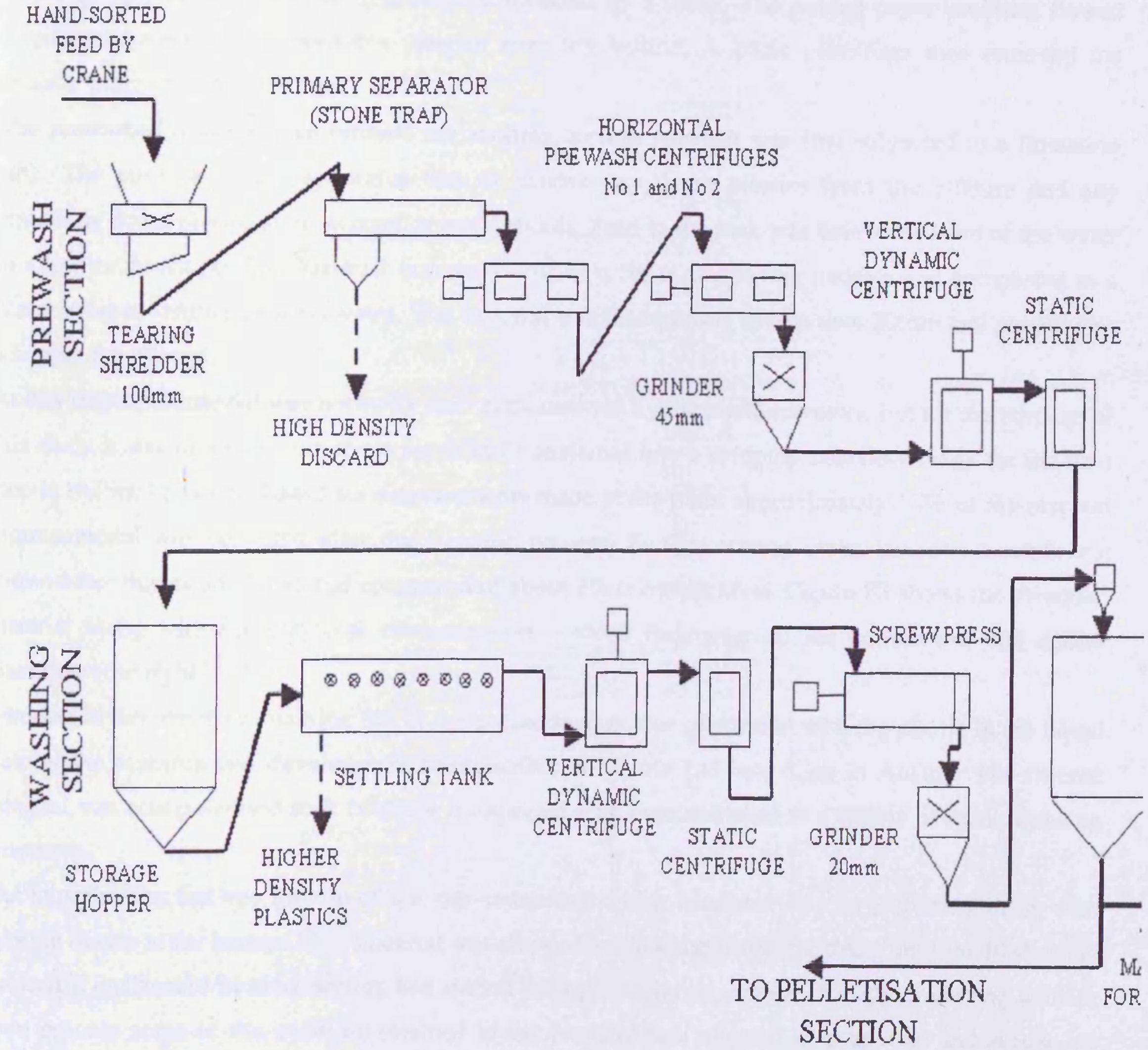


Figure F2 Schematic of the two-stage washing process.

The baled material from the sourcing process was split and fed into a primary tearing shredder by a crane. At the loading stage, the larger pieces of contamination, such as blocks of wood, were removed by the operator, allowing only the film material into the shredder. The shredder then reduced the material into pieces approximately 100mm in length. A tearing shredder was used as it can handle hard materials such as stones without sustaining damage.

The shredded material was then carried via a conveyor into a stone trap, which subjected it to a series of horizontal air and water jets. This allowed the lighter film material across the trap, whilst heavier particles, such as stones and metallic objects sank into the trap. The trap was periodically emptied via a discharge hopper.

Two prewash centrifuges were used to remove small particles and soluble material; it also started the pulping of paper products. The material then travelled into a screw grinder where it was reduced to a strip length of around 45mm. Finer blades could be used at this stage because harder objects such as stones had been removed.

A dynamic centrifuge was then used to remove most of the paper and cardboard from the mixture, which comprised of a vertical centrifuge surrounded by a mesh. The pulped paper products flowed through the mesh whilst insoluble plastics were left behind. A static centrifuge then removed the process water from the mixture.

The prewashed material then entered the washing section where it was first subjected to a floatation tank. The purpose of this apparatus was to remove any dense plastics from the mixture and any remaining dense objects such as smaller metal shards. Feed to the tank was below the level of the water to allow sufficient mixing. Material was drawn off by a series of rotating paddles and compacted in a screw press to remove process water. The material was then ground to less than 20mm and passed into a hopper for storage.

At this stage the material was normally melt agglomerated by the plant operators, but for the purpose of this study it was diverted from the process and transferred into a shipping container ready for the next step in the trial process. Based on measurements made at the plant approximately 73% of the original input material was collected after the cleaning process. Further sorting under laboratory conditions showed that this cleaned material comprised of about 3% contamination. Figure F3 shows the shredded material along with some typical contamination – wood fragments on the bottom left and denser plastics on the right.

Filtering to remove the remaining 3% of the contamination was performed with the plastic in the liquid state at the research and development headquarters of Erema Ltd near Linz in Austria. The filtered material was also pelletised so it could be transported with ease and used in a variety of manufacturing processes.

The material was fed into the top of a cutter-compactor which consisted of a large vertical drum with rotating blades at the bottom. The material was allowed to circulate inside the drum until the blades had reduced it in size and friction-heating had started the agglomeration process. By agglomerating with an open process some of the moisture retained in the material was allowed to evaporate and escape, as well as gasses generated from the contamination, which reduced the amount of gas bubbles in the final product.

The material was then fed directly into an extruder. As the material was partially agglomerated at this stage the length of the screw could be reduced, therefore reducing the residence time and thermal degradation during the extrusion process. Once through the extruder the plastic was molten and was transported via the pressure exerted by the screw.

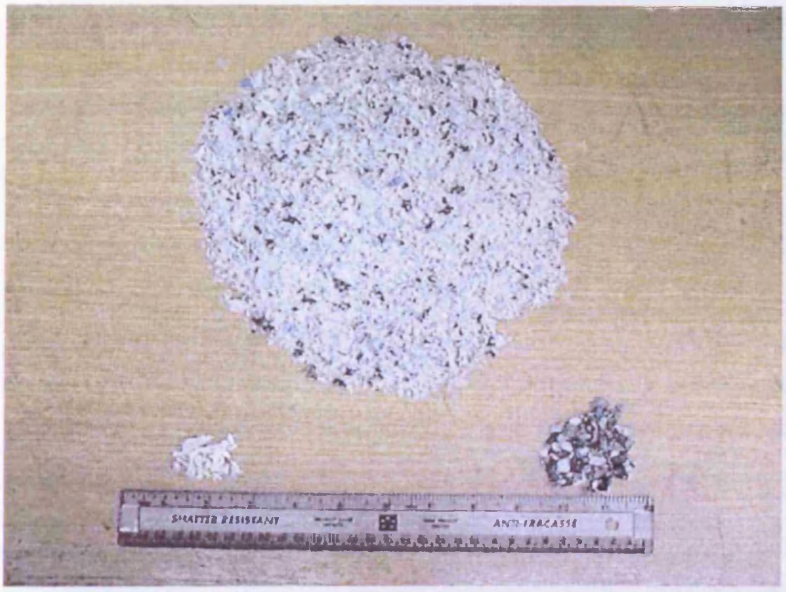


Figure F3 Shredded film (20mm) and typical contamination

## 2.2. Melt Filtering and Agglomeration

The filtration of the plastic mixture, which still contained contamination, was done via one of two techniques to evaluate their suitability in terms of cleaning ability and ease of operation:

1. A coarse wire mesh filter.
2. A laser filter (so called as the tiny holes in the filter are laser-drilled)

The filtering techniques were evaluated separately to test their performance of removing impurities from the molten plastic, along with their potential to clog due to the presence of these impurities.

The filtration of heavily contaminated material was difficult since the wire mesh filters quickly block and must be changed at short intervals. This is labour intensive and may reduce plant output. The Erema equipment comprised of a screen changer using four separate filters; the pressure rise associated with filter blocking triggered a backflushing process where the material flow was reversed by a system of hydraulically operated valves and the contaminants on the filter were flushed to waste.

An alternative approach, which is very effective with "soft" contaminants such as wood and paper, is the laser filter. In this system, the wire mesh screens were replaced with thicker steel plates, which are laser drilled to form the filters. Two filter plates are mounted back to back, and material was fed into the space between them. A rotating scraper in this space continuously cleared the filters, which are circular, breaking up "soft" material such as wood so that some eventually passes through the filter. This process operates continuously with no need for screen changes and a reduced volume of waste compared to conventional wire mesh screens. An advantage of this approach is that screen changes are not required, reducing labour and avoiding disruption to subsequent process stages through stoppages and air entrapment during screen changes.

The backflush mesh filter screen changer was effective in processing the material but frequent screen changes were required despite the backflushing system, which also resulted in the rejection of large quantities of material as waste. Initially a 100 micron filter was used but this blocked immediately and was replaced by a 300 micron filter, which required replacing at approximately 10 minute intervals. A contaminated filter is shown in Figure F4. Product output was 204 kg/hr, together with 22 kg/hr of waste from the backflushing process, a loss of 10.8%.

The Laser Filter system operated satisfactorily with no such blocking problems, producing an output of 284 kg/hr with 7.4 kg/hr of waste, i.e. a loss of only 2.6%. Therefore the laser filter system provided a swifter operation and a more efficiently filtered product.

Operation using the backflush screen changer system was possible but inefficient due to the frequent screen changes required. However, the Laser Filter system was very effective, producing only 2.6% waste and operating satisfactorily throughout the trial. A potential problem with this system is the danger of rapid wear due to grit in the feed material, but it would appear that the washing process was effective in removing contamination. This in any case did not appear to be present in significant quantities in the feed material. The filtered material was then pelletised and fed into bags ready for transport to the production stage.

Figure F4 Blocked 300 micron wire mesh filter and contamination

## 2.3. Extrusion and Production

Once in the pelletised state it was accepted that the material could be manufactured into new polyethylene products in a conventional manner. To evaluate its suitability for such processing the material was put through a number of manufacturing procedures, namely injection moulding, sheet extrusion of 1.5mm thickness and film blowing. Only film blowing will be covered in this paper as it is the most demanding application (because the thickness is so small) and it was the form in which the waste material was received at the input to the whole recycling process.

Film blowing was carried out by kind permission of Frank Mercer and Son Ltd, Bolton, UK. Around 230 kg of material was extruded through a 4 metre width line. The film was produced using a blown extruder operating at a thickness of 250 micron. Observations by plant workers described the material as being of acceptable quality for the process, with no serious problems occurring during the trail run. Further evaluation showed that the melt flow index (a measure of the plastic's viscosity when in the molten state) was slightly lower than expected, but this could be easily rectified by blending it with less viscous polymers. Figure F5 is a photograph of the blown film.

Figure F5 Blown film of 250 micron thickness.

Tensile tests were carried out on the film in accordance with BS EN ISO 527-3: 1995, using specimen type 5. Samples were cut in the longitudinal (process) direction and additional samples were cut in the transverse direction, in order to determine whether there was a difference in properties in the different directions. The material was then compared to the product normally produced at the Mercer plant.

## 3. Results

Figure F6 shows the ultimate tensile strength (UTS) and maximum elongation of the trial material in the longitudinal and transverse directions. Also shown is the material that was normally produced in the Mercer plant as a comparison.

The data shows that the trial material is comparable to the standard damp-proof film in terms of maximum elongation. It has a higher UTS in both directions, with the strongest being in the transverse direction. This data was then compared to the mechanical requirements of British Standards for other film products to determine which markets were potentially available for the recycled film. The recycled material met standards for agricultural (silage) film BS7476: 1991, which requires a minimum tensile strength of 15MPa and a minimum elongation of 450%, and BS6642: 1985 for refuse sacks, which requires a minimum tensile strength of 13.8MPa and an elongation of 200%.

In terms of processing costs, economic data was gathered at every stage of the trial such that a model could be built to express the financial costs of this operation. The economics were found to be favourable, provided parameters such as contamination, input material cost and product selling price were carefully controlled. More details of this economic analysis can be found in further studies made by the authors [4].

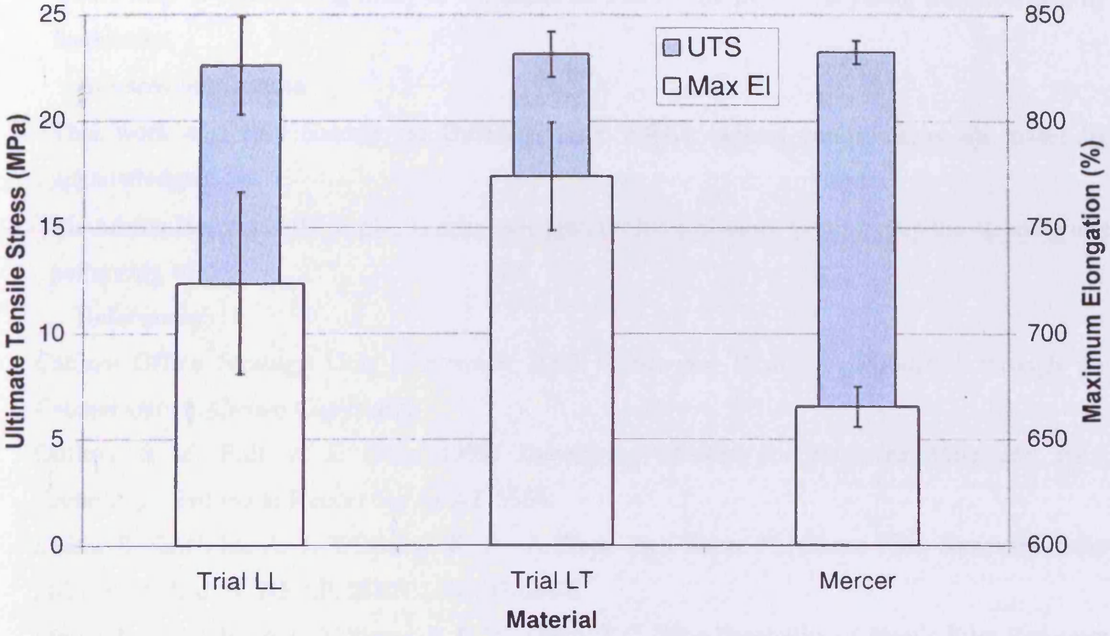


Figure F6 Tensile testing results of various types of film made from the process.

## 4. Discussion and Conclusion

- The four step process presented herein for the sourcing, washing, filtering and re-processing of plastic film has shown that it is possible to take a low-quality waste plastic film product and recycle it into a new film product that can be considered to be of high-quality economic value.
- Melt-filtering was found to be an effective way of removing the final parts of waste material from the plastic. The laser filter system was the most efficient at removing contamination, as well as requiring the least amount of maintenance.
- Although landfill is still the main destination for plastic film in the UK [5] such a recycling process could potentially have an effect on the amount of film disposed of in landfills.
- The work was carried out at four different sites and has shown that an operation which combines each of these steps in series can produce a saleable product. By using the expertise of the business consulted at each step, a picture can be built as to the requirements of this recycling process.
- To control the economics of the process, proximity is a critical factor. Siting the facility close to the waste source is a useful way of keeping overheads down. Logistics costs are particularly significant in plastic film as it has such a low bulk density [4,6] meaning that it costs more per tonne to haul film products than virtually any other waste product.
- Generally speaking industry sources prefer to work with waste product that have far less contamination that the material used in this study. Many reasons are cited, such as potential damage cause to manufacturing equipment from contamination and the risks involved with the sensitive economics of washing plants.

- At present there is no method of standardisation when it comes to identifying mixed plastic waste. A system for expressing the composition and contamination of a batch of plastics waste would help in overcoming many of the obstacles that inhibit plastic recycling from low quality feedstocks.

## 5. Acknowledgements

- This work was part funded via Biffaward and WRAP, whose contributions are gratefully acknowledged.
- Mr Adrian Horrocks of Norplas is acknowledged for his assistance in setting up the cleaning and pelletising trials.

## 6. References

1. Cabinet Office Strategy Unit (November 2002) *Waste not Want not.* Published through the Cabinet Office. Crown Copyright.
2. Ogilvie, S M, Poll, A J. (May 1999) *Developing Markets for Recycled Materials.* AEA Technology Technical Report No AEAT-5538.
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4. Marsh, R, Griffiths, A J, Williams, K P, Woollam, T C. "The Feasibility of Plastic Film Recovery From Waste Sources,". 19th International Conference on Solid Waste Technology and Management, March 2004.
5. DETR (2000) Waste Strategy 2000 England and Wales (Parts 1 & 2) HMSO.
6. Institute of Waste Management, *Materials Recovery Facilities*, CIWM [2000], ISBN 0902944576.

# Appendix G – Materials testing standards

|  |  |  |
|---|---|---|
| Extracts from : | BS EN ISO 1133 : 2000 | (Melt flow index) |
|  | BS EN ISO 527-3 : 1996 | (Tensile properties) |

BRITISH STANDARD

BS EN
ISO 1133:2000
BS 2782-7:
Method 720A:
1997

*Incorporating Amendment No. 1 to BS 2782-7: Method 720A:1997 (renumbers the BS as BS EN ISO 1133:2000)*

# Plastics — Determination of the melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) of thermoplastics (ISO 1133:1997)

The European Standard EN ISO 1133:1999 has the status of a British Standard

ICS 83.080.20

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 1133

May 1999

ICS 83.080.20

English version

# Plastics — Determination of the melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) of the thermoplastics

(ISO 1133:1997)

Plastiques — Détermination de l'indice de fluidité à chaud des thermoplastiques, en masse (MFR) et en volume (MVR)
(ISO 1133:1997)

Kunststoffe- Bestimmung der Schmelze-Massefließrate (MFR) und der Schmelze-Volumenfließrate (MVR) von Thermoplasten
(ISO 1133:1997)

This European Standard was approved by CEN on 16 April 1999.
CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and biliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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**Central Secretariat: rue de Stassart 35, B-1050 Brussels**

Ref. No. EN ISO 1133:1999 E

INTERNATIONAL
STANDARD

ISO
1133

Third edition
1997-01-15

# Plastics — Determination of the melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) of thermoplastics

*Plastiques — Détermination de l'indice de fluidité à chaud des thermoplastiques, en masse (MFR) et en volume (MVR)*

Reference number
ISO 1133:1997(E)

## 1 Scope

1.1 This International Standard specifies a method for the determination of the melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) of thermoplastic materials under specified conditions of temperature and load. Normally, the test conditions for measurement of melt flow rate are specified in the material standard with a reference to this International Standard. The test conditions normally used for thermoplastics are listed in annexes A and B. The melt volume-flow rate will normally be found useful when comparing filled and unfilled thermoplastics. The melt flow rate can now be determined by automatic measurement provided the melt density at the test temperature is known.

This method is not applicable to thermoplastics for which the rheological behaviour is affected by phenomena such as hydrolysis, condensation or crosslinking.

1.2 The melt mass-flow rate and melt volume-flow rate of thermoplastics are dependent on the rate of shear. The rates of shear in this test are much smaller than those used under normal conditions of fabrication, and therefore data obtained by this method for various thermoplastics may not always correlate with their behaviour in actual use. Both methods are useful in quality control.

## 2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 468:1982, *Surface roughness — Parameters, their values and general rules for specifying requirement.*

ISO 1622-1:1994, *Plastics — Polystyrene (PS) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 1872-1:1993, *Plastics — Polyethylene (PE) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 1873-1:1995, *Plastics — Polypropylene (PP) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 2580-1:1990, *Plastics — Acrylonitrile/butadiene/styrene (ABS) moulding and extrusion materials — Part 1: Designation.*

ISO 2897-1:1990, *Plastics — Impact-resistant polystyrene (SB) moulding and extrusion materials — Part 1: Designation.*

ISO 4613-1:1993, *Plastics — Ethylene/vinyl acetate (E/VAC) moulding and extrusion materials — Part 1: Designation and specification.*

ISO 4894-1:1990, *Plastics — Styrene/acrylonitrile (SAN) copolymer moulding and extrusion materials — Part 1: Designation.*

ISO 6402-1:1990, *Plastics — Impact-resistant acrylonitrile/styrene moulding and extrusion materials (ASA, AES, ACS), excluding butadiene-modified materials — Part 1: Designation.*

ISO 6507-1:—[1], *Metallic materials — Vickers hardness test — Part 1: Test method.*

ISO 7391-1:—[2], *Plastics — Polycarbonate moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 8257-1:—[3], *Plastics — Poly(methyl methacrylate) (PMMA) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 8986-1:1993, *Plastics — Polybutene (PB) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

ISO 9988-1:1991, *Plastics — Polyoxymethylene (POM) moulding and extrusion materials — Part 1: Designation.*

ISO 10366-1:1993, *Plastics — Methyl methacrylate/acrylonitrile/butadiene/styrene (MABS) moulding and extrusion materials — Part 1: Designation system and basis for specifications.*

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[1] To be published. (Revision of ISO 6507-1:1982, ISO 6507-2:1983, ISO 6507-3:1989, ISO 409-1:1982, ISO 409-2:1983 and ISO/DIS 409-3)

[2] To be published. (Revision of ISO 7391-1:1987)

[3] To be published. (Revision of ISO 8257-1:1987)

## 3 Apparatus

### 3.1 Basic apparatus

3.1.1 The apparatus is basically an extrusion plastometer operating at a fixed temperature. The general design is as shown in Figure 1. The thermoplastic material, which is contained in a vertical cylinder, is extruded through a die by a loaded piston. The apparatus consists of the following essential parts:

3.1.2 *Cylinder,* fixed in a vertical position. The cylinder shall consist of a material resistant to wear and corrosion up to the maximum temperature of the heating system and shall be inert to the test sample. For particular materials, measurements may be required at temperatures up to 450 °C. The cylinder length shall be between 115 mm and 180 mm and the internal diameter 9,550 mm ± 0,025 mm. The base of the cylinder shall be thermally insulated in such a way that the area of the exposed metal is less than 4 cm$^2$, and it is recommended that an insulating material such as $Al_2O_3$ ceramic fibre or another suitable material be used in order to avoid sticking of the extrudate.

The bore shall be hardened to a Vickers hardness of no less than 500 (HV 5 to HV 100) (see ISO 6507-1) and shall have a surface roughness less than $R_a$ (arithmetic mean discrepancy) = 0,25 µm (see ISO 468). If necessary, a piston guide shall be provided to keep friction caused by misalignment of the piston down to a level at which the actual load does not differ from the nominal load by more than ± 0,5 %.

3.1.3 *Steel piston,* having a working length at least as long as the cylinder. The piston shall have a head 6,35 mm ± 0,10 mm in length. The diameter of the head shall be less than the internal diameter of the cylinder by 0,075 mm ± 0,010 mm. The upper edge shall have its sharp edge removed. Above the head, the piston shall be relieved to about 9 mm diameter. A stud may be added at the top of the piston to support the removable load, but the piston shall be thermally insulated from the load. Along the piston stem, two thin annular reference marks shall be scribed 30 mm apart and so positioned that the upper one is aligned with the top of the cylinder when the distance between the lower edge of the piston head and the top of the die is 20 mm. These annular marks on the piston are used as reference points during the determination (see **6.3** and **7.4**).

To ensure satisfactory operation of the apparatus, the cylinder and the piston shall be made of materials of different hardness. It is convenient for ease of maintenance and renewal to make the cylinder of the harder material.

The piston may be either hollow or solid. In tests with lower loads, the piston shall be hollow, otherwise it may not be possible to obtain the lowest prescribed load. When the test is performed with the higher loads, the hollow piston is not desirable, as the higher load may distort such a piston. In such tests, a solid piston or a hollow piston with suitable guides shall be used. When using this latter modification, it is essential that the heat loss along the piston, which is generally longer than usual, does not alter the test temperature of the material.

3.1.4 ***Temperature-control system***

For all cylinder temperatures that can be set, the temperature control shall be such that between the die and the permissible filling height of the barrel, the temperature differences measured at the wall do not exceed those given in Table 1 throughout the duration of the test.

NOTE The wall temperature may be measured with thermocouples of Pt thermometers embedded in the wall. If the apparatus is not equipped in this way, the temperature is measured in the melt at a certain distance from the wall, depending on the type of thermometer used.

The temperature-control system shall allow the test temperature to be set in steps of 1 °C or less.

**Table 1 — Maximum allowable variation in temperature with distance and with time**

| Test temperature, u °C | Variation in temperature, °C | |
|---|---|---|
| | with distance | with time |
| u < 200 | ± 1 | ± 0,5 |
| 200 < u < 300 | ± 1,5 | ± 1,0 |
| u > 300 | ± 2 | ± 1,5 |

3.1.5 *Dies,* made of tungsten carbide or hardened steel, 8,000 mm ± 0,025 mm in length. The interior shall be circular, straight and uniform in diameter such that in all positions it is within 0,005 mm of a true cylinder of nominal diameter 2,095 mm.

The bore shall be hardened to a Vickers hardness of no less than 500 (HV 5 to HV 100) (see ISO 6507-1) and shall have a surface roughness less than $R_a$ (arithmetic mean discrepancy) = 0,25 µm (see ISO 468). The die shall not project beyond the base of the cylinder (see Figure 1) and shall be mounted so that its bore is co-axial with the cylinder bore.

3.1.6 ***Means of setting and maintaining the cylinder truly vertical***

A two-directional bubble level, set normal to the cylinder axis, and adjustable supports for the apparatus are suitable for the purpose.

NOTE This is to avoid excessive friction caused by the piston or bending under heavy loads. A dummy piston with a spirit level on its upper end is a suitable means of checking conformity with this requirement.

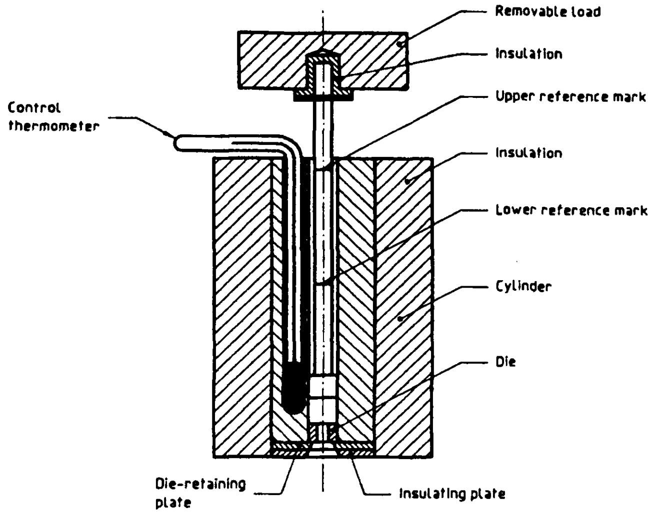

**Figure 1** — **Typical apparatus for determining melt flow rate (showing one of the possible methods of retaining the die and one type of piston)**

3.1.7 *Removable load,* on the top of this piston, which consists of a set of weights which may be adjusted so that the combined mass of the load and the piston gives the selected nominal load to an accuracy of 0,5 %. An alternative mechanical loading device may be used for higher loads.

### 3.2 Accessory equipment

3.2.1 *General*

3.2.1.1 *Equipment for introducing test samples into the cylinder,* consisting of a packing rod made of non-abrasive material.

3.2.1.2 *Cleaning equipment*

3.2.1.3 *Mercury-in-glass thermometer* (calibration thermometer) or another temperature-measuring device. This measuring device shall be calibrated to permit temperature measurement to ± 0,5 °C at the temperature and immersion conditions to be used when calibrating the temperature-control system in accordance with **5.15.1**.

3.2.2 ***For procedure A***

3.2.2.1 *Cutting tool,* for cutting off extruded sample. A sharp-edged spatula has been found suitable.

3.2.2.2 *Timer,* accurate to ± 0,1 s.

3.2.2.3 *Balance,* accurate to ± 0,5 mg.

3.2.3 ***For procedure B***

*Measurement equipment,* for the automatic measurement of distance and time for the piston movement.

## 4 Test sample

4.1 The test sample may be in any form that can be introduced into the bore of the cylinder, for example powder, granules or strips of film.

NOTE Some materials in powder form do not give a bubble-free filament if they are not previously compressed.

4.2 The test sample shall be conditioned and, if necessary, stabilized prior to the test, in accordance with the material specifications.

## 5 Temperature calibration, cleaning and maintenance of the apparatus

### 5.1 Calibration of the temperature-control system

**5.1.1** It is necessary to verify regularly the accuracy of the temperature-control system (3.1.4). For this purpose, adjust the temperature-control system until the cylinder will remain at the required temperature as indicated by the control thermometer. Preheat a calibration thermometer (3.2.1.3) to the same temperature. Then charge the cylinder with a quantity of the material to be tested, or a material representative thereof (see 5.1.2), using the same technique as for a test (see 6.2). Four minutes after completing the charging of the material, introduce the calibration thermometer into the sample chamber and immerse it in the material therein until the tip of the bulb is 10 mm from the upper face of the die. After a further interval of not less than 4 min and not more than 10 min, correct the temperature indicated by the control thermometer by algebraic addition of the difference between the temperatures read on the two thermometers. It is also necessary to verify the temperature profile along the cylinder. For this, measure the temperature of the material every 10 mm up to a point 60 mm above the upper face of the die. The maximum variation between the extreme values shall conform to Table 1.

**5.1.2** It is essential that the material used during calibration be sufficiently fluid to permit, for instance, a mercury-filled thermometer bulb to be introduced without excessive force or risk of damage. A material with an MFR of greater than 45 g/10 min (2,16 kg load) at the calibration temperature has been found suitable.

If such a material is used for calibration purposes in place of a more viscous material which is to be tested, the dummy material shall have a thermal diffusivity similar to that of the material to be tested, so that warm-up behaviour is similar. It is necessary that the quantity charged for calibration be such that, when the calibration thermometer is subsequently introduced, the appropriate length of the thermometer stem is immersed for accurate temperature measurement. This can be checked by inspecting the upper limit of the material coating the end of the calibration thermometer, removing the thermometer from the cylinder if necessary.

### 5.2 Cleaning the apparatus

The apparatus shall be cleaned thoroughly after each determination. The cylinder may be cleaned with cloth patches. The piston shall be cleaned while hot with a cloth. The die may be cleaned with a closely fitting brass reamer or wooden peg. Pyrolytic cleaning in a nitrogen atmosphere at about 550 °C may also be used. Abrasives or materials likely to damage the surface of the piston, cylinder or die shall not be used. Take care that the cleaning procedure used does not affect the die dimensions or surface finish.

If solvents are used to clean the cylinder, take care that any effect they may have on the next determination is negligible.

NOTE It is recommended that, at fairly frequent intervals, for example once a week for instruments in constant use, the insulating plate and the die-retaining plate, if fitted as in Figure 1, be removed, and the cylinder cleaned throughout.

## 6 Procedure A

**6.1** Clean the apparatus (see 5.2). Before beginning a series of tests, ensure that the cylinder (3.1.2) has been at the selected temperature for not less than 15 min.

**6.2** Then charge the cylinder with 3 g to 8 g of the sample according to the anticipated melt flow rate (see, as a guide, Table 2). During the charging, compress the material with the packing rod (3.2.1.1), using hand pressure. To ensure a charge as free from air as possible for material susceptible to oxidative degradation, complete the charging process in 1 min. Put the piston, loaded or unloaded according to the flow rate of the material, in the cylinder.

If the melt flow rate of the material is high, that is, more than 10 g/10 min, the loss of sample during preheating will be appreciable. In this case, use an unloaded piston or one carrying a smaller weight during the preheating period, and then change to the desired weight at the end of the 4 min preheating time. In the case of very high melt flow rates, a die-plug may be necessary.

**Table 2**

| Melt flow rate[1)] g/10 min | Mass of test sample in cylinder[2)] g | Extrudate cut-off time-interval s |
|---|---|---|
| > 0,1 but < 0,5 | 3 to 5 | 240 |
| > 0,5 but < 1 | 4 to 6 | 120 |
| > 1 but < 3,5 | 4 to 6 | 60 |
| > 3,5 but < 10 | 6 to 8 | 30 |
| > 10 | 6 to 8 | 5 to 15[3)] |

[1)] It is recommended that melt a flow rate should not be measured if the value obtained in this test is less than 0,1 g/10 min or greater than 100 g/10 min.

[2)] When the density of the material is greater than 1,0 g/cm$^3$, it may be necessary to increase the mass of the test portion.

[3)] To achieve adequate repeatability when testing materials having an MFR greater than 25 g/10 min, it may be necessary either to control and measure cut-off intervals automatically to less than 0,1 s or to use procedure B.

**6.3** Four minutes after completing the introduction of the test sample, during which time the temperature shall have returned to that selected, place the selected load on the piston, if it was unloaded or under-loaded. Allow the piston to descend under gravity, until a bubble-free filament is extruded; this may be done before or after loading, depending on the actual viscosity of the material. The time for this operation shall not exceed 1 min. Cut off the extrudate with the cutting tool (**3.2.2.1**), and discard. Continue to allow the loaded piston to descend under gravity. When the lower reference mark has reached the top edge of the cylinder, start the timer (**3.2.2.2**), and simultaneously cut off the extrudate with the cutting tool and again discard.

Then collect successive cut-offs in order to measure the extrusion rate at time-intervals, depending on the melt flow rate, so chosen that the length of a single cut-off is not less than 10 mm and preferably between 10 mm and 20 mm (see cut-off time-intervals in Table 2 as a guide).

For low values of MFR (and MVR) and/or materials which exhibit a relatively high degree of die swell, it may not be possible to take a cut-off with a length of 10 mm or more within the maximum time-interval of 240 s. In such cases, procedure A may be used, but only if the mass of each cut-off obtained in 240 s is greater than 0,04 g. If not, procedure B shall be used.

Stop cutting when the upper mark on the piston stem reaches the top edge of the cylinder. Discard any cut-off containing visible air bubbles. After cooling, weigh individually, to the nearest 1 mg, the remaining cut-offs, which shall number at least three, and calculate their average mass. If the difference between the maximum and the minimum value of the individual weighings exceeds 15 % of the average, discard the result and repeat the test on a fresh portion of the sample.

The time between charging the cylinder and the last measurement shall not exceed 25 min.

**6.4** The melt mass-flow rate (MFR), expressed in grams per 10 min, is given by the equation

$$\mathrm{MFR}(\theta, m_{\mathrm{nom}}) = \frac{t_{\mathrm{ref}} \cdot m}{t}$$

where

$\theta$ is the test temperature, in degrees Celsius;

$m_{\mathrm{nom}}$ is the nominal load, in kilograms;

$m$ is the average mass, in grams, of the cut-offs;

$t_{\mathrm{ref}}$ is the reference time (10 min), in seconds (600 s);

$t$ is the cut-off time-interval, in seconds.

Express the result to two significant figures and record the test conditions used (e.g. 190/2,16).

## 7 Procedure B

### 7.1 Principle

The melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) are determined by using either of the following two principles:

a) measurement of the distance the piston moves in a specified time;

b) measurement of the time in which the piston moves a specified distance.

### 7.2 Optimum measurement accuracy

For repeatable determination of MFR between 0,1 g/10 min and 50 g/10 min or MVR between 0,1 cm$^3$/10 min and 50 cm$^3$/10 min, the movement of the piston has to be measured to the nearest ± 0,1 mm and the time to an accuracy of 0,1 s.

### 7.3 Pretreatment

Follow procedure A specified in **6.1** to **6.3** (to end of first paragraph).

### 7.4 Determination

**7.4.1** When the lower reference mark has reached the top edge of the cylinder, start the automatic measurement.

**7.4.2** Take measurements as follows:

a) If using the principle given in **7.1** a), measure the distance moved by the piston at predetermined times.

b) If using the principle given in **7.1** b), measure the times taken by the reference mark to cover a specified distance.

Stop the measurement when the upper mark on the piston stem reaches the top edge of the cylinder.

**7.4.3** The time between charging the cylinder and the last measurement shall not exceed 25 min.

### 7.5 Expression of results

**7.5.1** The melt volume-flow rate (MVR), expressed in cubic centimetres per 10 min, is given by the equation

$$\mathrm{MVR}(\theta, m_{\mathrm{nom}}) = \frac{A \cdot t_{\mathrm{ref}} \cdot l}{t} = \frac{427 l}{t}$$

where

| | |
|---|---|
| $\theta$ | is the test temperature, in degrees Celsius; |
| $m_{\mathrm{nom}}$ | is the nominal load, in kilograms; |
| $A$ | is the mean cross-sectional area, in square centimetres of the piston and the cylinder (= 0,711 cm$^2$); |
| $t_{\mathrm{ref}}$ | is the reference time (10 min), in seconds (600 s); |
| $t$ | is the predetermined time of measurement [see **7.4.2** a)] or the mean value of the individual time measurements [see **7.4.2** b)], in seconds; |
| $l$ | is the predetermined distance moved by the piston [see **7.4.2** b)] or the mean value of the individual distance measurements [see **7.4.2** a)], in centimetres. |

**7.5.2** The melt mass-flow rate (MFR), expressed in grams per 10 min, is given by the equation

$$\mathrm{MFR}(\theta, m_{\mathrm{nom}}) = \frac{A \cdot t_{\mathrm{ref}} \cdot l \cdot \rho}{t} = \frac{427 \cdot l \cdot \rho}{t}$$

where

$\theta$, $m_{\mathrm{nom}}$, $A$, $t_{\mathrm{ref}}$, $t$ and $l$ are as defined in **7.5.1**;

$\rho$ is the density, in grams per cubic centimetre, of the melt at the test temperature and is given by the equation

$$\rho = \frac{m}{0,711 l}$$

$m$ being the mass, determined by weighing, of extrudate expelled by a piston movement of $l$ cm.

**7.5.3** Express the result to two significant figures and record the test conditions used (e.g. 190/2,16).

## 8 Flow rate ratio (FRR)

The relationship between two values of MFR (or MVR) is called the flow rate ratio, e.g.

$$\mathrm{FRR} = \frac{\mathrm{MFR}\ (190/21{,}6)}{\mathrm{MFR}\ (190/2{,}16)}$$

It is commonly used as an indication of the way in which the rheological behaviour is influenced by the molecular mass distribution of the material.

NOTE The conditions to be used for the determination of the flow rate ratio are given in the appropriate material standards.

## 9 Precision

When the method is used with certain materials, consideration shall be given to the factors leading to a decrease in repeatability. Such factors include the following:

a) thermal degradation or crosslinking of the material, causing the melt flow rate to change during the preheating or test period (powdered materials requiring long preheating times are sensitive to this effect and, in certain cases, the inclusion of stabilizers is necessary to reduce the variability);

b) filled or reinforced materials, where the distribution or orientation of the filler may affect the melt flow rate.

The precision of the method is not known because interlaboratory data are not available. A single precision statement would not be suitable because of the number of materials covered. However, a coefficient of variation of about ± 10 % could be expected.

## 10 Test report

The test report shall include the following particulars:

a) a reference to this International Standard;

b) all details necessary for the complete identification of the test sample, including the physical form of the material with which the cylinder was charged;

c) the details of conditioning;

d) the details of any stabilization (see **3.44.2**);

e) the temperature and load used in the test;

f) for procedure A, the masses of the cut-offs and the cut-off times-intervals or, for procedure B, the predetermined time of measurement or distance moved by the piston and the corresponding measured values of the distance moved by the piston or time of measurement;

g) the melt mass-flow rate, in grams per 10 min, or the melt volume-flow rate, in cubic centimetre per 10 min, expressed to two significant figures (when more than one value has been obtained, all the individual values shall be reported);

h) if desired, the flow rate ratio (FRR);

i) a report of any unusual behaviour of the test sample, such as discoloration, sticking, extrudate distortion or unexpected variation in melt flow rate;

j) the date of the test.

## Annex A (normative)
## Test conditions for melt flow rate determination

The conditions used shall be as indicated in the appropriate material designation or specification. Table A.1 indicates test conditions that have been found useful.

Table A.1

| **Conditions** (code letter) | **Test temperature, u** °C | **Nominal load (combined), $m_{nom}$** kg |
|---|---|---|
| A | 250 | 2,16 |
| B | 150 | 2,16 |
| D | 190 | 2,16 |
| E | 190 | 0,325 |
| F | 190 | 10,00 |
| G | 190 | 21,60 |
| H | 200 | 5,00 |
| M | 230 | 2,16 |
| N | 230 | 3,80 |
| S | 280 | 2,16 |
| T | 190 | 5,00 |
| U | 220 | 10,00 |
| W | 300 | 1,20 |
| Z | 125 | 0,325 |

NOTE If, in the future, conditions other than those listed in this table are necessary, e.g. for new thermoplastics, only the loads already in use shall be chosen. Temperatures shall also be selected from those already in the table. If absolutely necessary, new temperatures might have to be taken because of the nature of the new thermoplastic. In this case, application to ISO/TC 61/SC 5 shall be made to include the new conditions. If approved, a suitable code-letter will provisionally be issued and the standard amended at the 5-year revision.

## Annex B (informative)
## Conditions in use for the designation of standards for thermoplastic materials

Table B.1 indicates test conditions that are currently specified in relevant International Standards. Other test conditions not listed here may be used, if necessary, for a particular material.

**Table B.1**

| International Standard (see clause 2) | Materials | Conditions (code letter) | Test temperature, $\theta$ °C | Nominal load (combined), $m_{nom}$ kg |
|---|---|---|---|---|
| ISO 1622-1 | PS | H | 200 | 5,00 |
| ISO 1872-1 | PE | D | 190 | 2,16 |
| ISO 1872-1 | PE | E | 190 | 0,325 |
| ISO 1872-1 | PE | G | 190 | 21,60 |
| ISO 1872-1 | PE | T | 190 | 5,00 |
| ISO 1873-1 | PP | M | 230 | 2,16 |
| ISO 2580-1 | ABS | U | 220 | 10,00 |
| ISO 2897-1 | PS-I | H | 200 | 5,00 |
| ISO 4613-1 | E/VAC | B | 150 | 2,16 |
| ISO 4613-1 | E/VAC | D | 190 | 2,16 |
| ISO 4613-1 | E/VAC | Z | 125 | 0,325 |
| ISO 4894-1 | SAN | U | 220 | 10,00 |
| ISO 6402-1 | ASA, ACS AES | U | 220 | 10,00 |
| ISO 7391-1 | PC | W | 300 | 1,20 |
| ISO 8257-1 | PMMA | N | 230 | 3,80 |
| ISO 8986-1 | PB | D | 190 | 2,16 |
| ISO 8986-1 | PB | F | 190 | 10,00 |
| ISO 9988-1 | POM | D | 190 | 2,16 |
| ISO 10366-1 | MABS | U | 220 | 10,00 |

BRITISH STANDARD

BS EN ISO
527-3:1996
BS 2782-3:
Method 326 E:
1996
*Incorporating Technical Corrigendum No. 1 and Corrigendum No. 1*

# Plastics — Determination of tensile properties —

## Part 3: Test conditions for films and sheets

The European Standard EN ISO 527-3:1995 has the status of a British Standard

Product code 00637413
ICS 83.140.10

British Standards

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

# EN ISO 527-3

August 1995

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ICS 83.140.00

Incorporating technical corrigenda June 1998 and April 2001

Descriptors: Plastics, films, plastic sheets, tests, determination, tensile properties, testing conditions, test specimens

English version

# Plastics — Determination of tensile properties — Part 3: Test conditions for films and sheets

(ISO 527-3:1995)

Plastiques — Détermination des propriétés en traction —
Partie 3: Conditions d'essai pour films et feuilles
(ISO 527-3:1995)

Kunstoffe — Bestimmung der Zugeigenschaften —
Teil 3: Prüfbedingungen für Folien und Tafeln
(ISO 527-3:1995)

This European Standard was approved by CEN on 1995-07-29. CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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**CEN**

European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

**Central Secretariat: rue de Stassart 36, B-1050 Brussels**

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Ref. No. EN ISO 527-3:1995 E

## 1 Scope

**1.1** This part of ISO 527 specifies the conditions for determining the tensile properties of plastic films or sheets less than 1 mm thick, based upon the general principles given in part 1.

NOTE For sheets greater than 1 mm thick, the user is referred to part 2 of this International Standard

**1.2** See ISO 527-1, subclause **1.2**.

**1.3** This part of ISO 527 is not normally suitable for determining the tensile properties of:

a) cellular materials;

b) plastics reinforced by textile fibres.

**1.4** See ISO 527-1, subclause **1.5**.

## 2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO 527. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO 527 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 527-1:1993, *Plastics — Determination of tensile properties — Part 1: General principles.*

ISO 4591:1992, *Plastics — Film and sheeting — Determination of average thickness of a sample, and average thickness and yield of a roll by gravimetric techniques (gravimetric thickness).*

ISO 4593:1993, *Plastics — Film and sheeting — Determination of thickness by mechanical scanning.*

## 3 Principle

See ISO 527-1, Clause 3.

## 4 Definitions

See ISO 527-1, Clause 4.

## 5 Apparatus

See ISO 527-1, Clause **5**, subject to the following additional requirements:

In 5.1.2, the tensile-testing machine shall be capable of maintaining the speeds of testing as specified in Table 1 of ISO 527-1. It is normal for films and sheets to be tested at a speed of 5 mm/min, 50 mm/min, 100 mm/min, 200 mm/min, 300 mm/min or 500 mm/min. The information contained in ISO 527-1, subclause 9.6, also applies.

In 5.1.5, when testing thin sheets or film material, the specimen shall not carry the weight of the extensometer.

In 5.2, devices complying with the requirements in ISO 4593 shall be used for measuring the thickness, except in the case of very thin film (less than 0,01 mm thick) or embossed film. In those cases, the thickness shall be determined by the method specified in ISO 4591. When ISO 4591 is used, the average thickness of the film sample shall be taken as the thickness of the test specimen.

## 6 Test specimens

### 6.1 Shape and dimensions

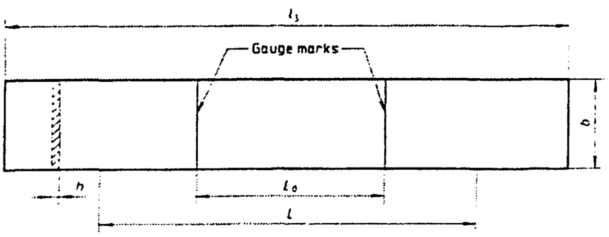
**6.1.1** The preferred form of test specimen for the determination of tensile properties by this method is a strip 10 mm to 25 mm wide and not less than 150 mm long (specimen type 2 — see Figure 1), having two parallel gauge marks, 50 mm apart, on the central portion of the specimen.

Some film materials have a very high elongation at break which may result in them being outside the stretching capacity of the testing machine. In such cases, it is permissible to reduce the initial distance between the grips to 50 mm.

**6.1.2** When required by the specification for the material under test or for routine quality-control tests, dumb-bell specimen types 5, 1B and 4 of the shape and dimensions shown in Figure 2, Figure 3 and Figure 4 may be used. These specimens are convenient to produce and permit rapid quality-control testing.

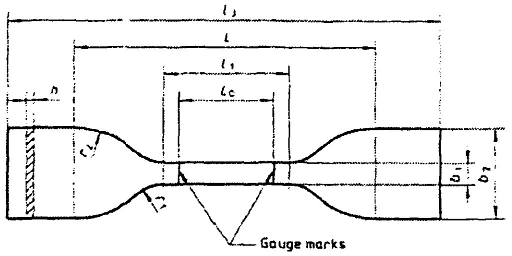
Specimen type 5 (Figure 2) is recommended for film and sheet with a very high strain at break. Specimen type 4 is recommended for other types of flexible thermoplastic sheet.

Specimen type 1B (Figure 3) is recommended for rigid sheets.



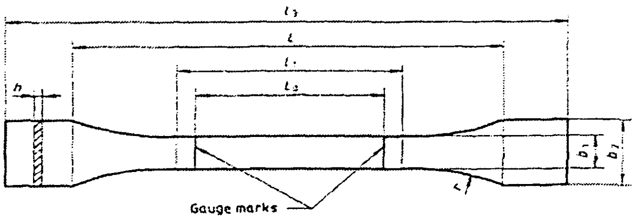
| | |
|---|---|
| $b$ | Width: 10 mm to 25 mm |
| $h$ | Thickness: ≤ 1 mm |
| $L_0$ | Gauge length: 50 mm ± 0,5 mm |
| $L$ | Initial distance between grips: 100 mm ± 5 mm |
| $l_3$ | Overall length: ≥ 150 mm |

Figure 1 — Specimen type 2



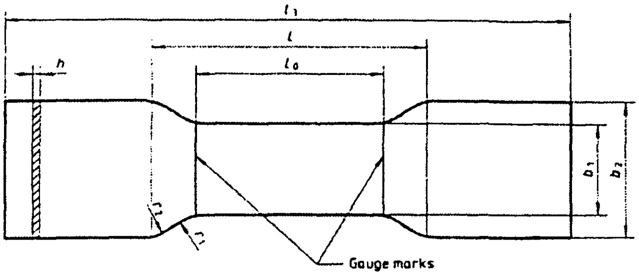
| | |
|---|---|
| $b_1$ | Width of narrow parallel-sided portion: 6 mm ± 0,4 mm |
| $b_2$ | Width at ends: 25 mm ± 1 mm |
| $h$ | Thickness: ≤ 1 mm |
| $L_0$ | Gauge length: 25 mm ± 0,25 mm |
| $l_1$ | Length of narrow parallel-sided portion: 33 mm ± 2 mm |
| $L$ | Initial distance between grips: 80 mm ± 5 mm |
| $l_3$ | Overall length: ≥ 115 mm |
| $r_1$ | Small radius: 14 mm ± 1 mm |
| $r_2$ | Large radius: 25 mm ± 2 mm |

Figure 2 — Specimen type 5



| | |
|---|---|
| $b_1$ | Width of narrow parallel-sided portion: 10 mm ± 0,2 mm |
| $b_2$ | Width at ends: 20 mm ± 0,5 mm |
| $h$ | Thickness: ≤ 1 mm |
| $L_0$ | Gauge length: 50 mm ± 0,5 mm |
| $l_1$ | Length of narrow parallel-sided portion: 60 mm ± 0,5 mm |
| $L$ | Initial distance between grips: 115 mm ± 5 mm |
| $l_3$ | Overall length: ≥ 150 mm |
| $r$ | Radius: ≥ 60 mm (recommended radius: 60,0 mm ± 0,5 mm) |

Figure 3 — Specimen type 1B



| | |
|---|---|
| $b_1$ | Width of narrow parallel-sided portion: 25,4 mm ± 0,1 mm |
| $b_2$ | Width at ends: 38 mm |
| $h$ | Thickness: ≤ 1 mm |
| $L_0$ | Gauge length: 50 mm ± 0,5 mm |
| $L$ | Initial distance between grips: 98 mm |
| $l_3$ | Overall length: 152 mm |
| $r_1$ | Small radius: 22 mm |
| $r_2$ | Large radius: 25,4 mm |

Figure 4 — Specimen type 4

### 6.2 Preparation of specimens

**6.2.1** The test specimens described in **6.1.1** shall be cut or punched so that the edges are smooth and free from notches; examination with a low-power magnifier is recommended to check the absence of notches. Razor blades, suitable paper cutters, scalpels or other devices capable of cutting the specimens to the proper width and producing straight, clean, parallel edges with no visible imperfections shall be used. Punch dies shall be kept sharp by regular honing, and a suitable backing material shall be used with punch dies to ensure a clean-cut edge.

**6.2.2** The test specimens described in **6.1.2** shall be obtained by the use of punch dies, using suitable backing material to ensure a clean-cut edge. Dies shall be kept sharp by regular honing, and the edges of the specimen shall be examined with a low-power magnifier to ensure the absence of notches. Discard any specimen with obvious imperfections on the cut edges.

### 6.3 Gauge marks

See ISO 527-1, subclause **6.3**.

The marking device used to produce the gauge marks shall have two parallel edges which are ground smooth and true, 0,05 mm to 0,10 mm wide at the edge and bevelled at an angle of not more than 15°. An ink stamp may also be used to apply ink to the area of the gauge marks, before or after producing them with the marking device, using an ink of a suitable contrasting colour that has no deleterious effect on the film being tested.

### 6.4 Checking the specimens

Discard any test specimen with obvious imperfections on the cut edges.

### 6.5 Anisotropy

The properties of certain types of film material may vary with direction in the plane of the film (anisotropy). In such cases, it is essential to prepare two groups of test specimens with their major axes respectively parallel and perpendicular to the direction of orientation of the film.

## 7 Number of specimens

See ISO 527-1, Clause **7**.

## 8 Conditioning

See ISO 527-1, Clause **8**.

## 9 Procedure

See ISO 527-1, Clause **9**.

## 10 Calculation and expression of results

See ISO 527-1, Clause **10**, except for "**10.3** Modulus calculation", and "**10.4** Poisson's ratio, $\mu$".

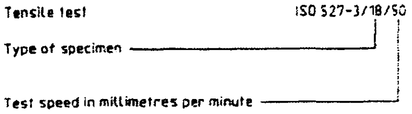
## 11 Precision

The precision of the test method is not known because inter-laboratory data are not available. When inter-laboratory data are obtained, a precision statement will be added at the following revision.

## 12 Test report

The test report shall include the following information:

a) a reference to this part of ISO 527, including the type of specimen and the test speed, written in the following format:



b) to q) see ISO 527-1, Clause **12**, b) to q).

# Appendix H - Test data and material images

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| Virgin LDPE 0 cycle | | 1 | 6.027 | 2.366 | 260 | 108 | 18.23 | | | | | |
| Virgin LDPE 0 cycle | | 2 | 5.921 | 2.095 | 235 | 80 | 18.94 | | | | | |
| Virgin LDPE 0 cycle | | 3 | 5.959 | 2.056 | 260 | 92 | 21.22 | | | | | |
| Virgin LDPE 0 cycle | | 4 | 5.927 | 2.046 | 215 | 108 | 17.73 | | | | | |
| Virgin LDPE 0 cycle | | 6 | 5.910 | 2.022 | 230 | 96 | 19.25 | | | | | |
| **Virgin LDPE 0 cycle** | 21/03/2003 | | | | **240** | **96.8** | **19.1** | **1.50** | **24.2** | **7.9** | **22250** | **175500** |
| Virgin LDPE 1 cycle | | 1 | 5.990 | 2.142 | 270 | 80 | 21.04 | | | | | |
| Virgin LDPE 1 cycle | | 2 | 5.926 | 2.013 | 235 | 88 | 19.70 | | | | | |
| Virgin LDPE 1 cycle | | 3 | 5.977 | 2.148 | 280 | 76 | 21.81 | | | | | |
| Virgin LDPE 1 cycle | | 4 | 5.881 | 2.031 | | 84 | | | | | | |
| Virgin LDPE 1 cycle | | 5 | 5.917 | 2.175 | 250 | 92 | 19.43 | | | | | |
| Virgin LDPE 1 cycle | | 6 | 5.982 | 2.080 | 275 | 72 | 22.10 | | | | | |
| **Virgin LDPE 1 cycle** | 25/03/2003 | | | | **262** | **82.0** | **20.8** | **1.18** | **28** | **8.3** | **21550** | **178500** |
| Virgin LDPE 2 cycle | | 1 | 5.819 | 2.116 | 235 | 72 | 19.09 | | | | | |
| Virgin LDPE 2 cycle | | 2 | 5.832 | 2.176 | 230 | 76 | 18.12 | | | | | |
| Virgin LDPE 2 cycle | | 3 | 5.929 | 2.162 | 260 | 72 | 20.28 | | | | | |
| Virgin LDPE 2 cycle | | 4 | 5.838 | 2.269 | 265 | 84 | 20.01 | | | | | |
| Virgin LDPE 2 cycle | | 5 | 5.804 | 2.189 | 225 | 72 | 17.71 | | | | | |
| Virgin LDPE 2 cycle | | 6 | 5.909 | 2.205 | 255 | 72 | 19.57 | | | | | |
| **Virgin LDPE 2 cycle** | 28/03/2003 | | | | **245** | **74.7** | **19.1** | **0.92** | **28.6** | **8.55** | **21700** | **185500** |
| Virgin LDPE 3 cycle | | 1 | 5.868 | 2.139 | 225 | 68 | 17.93 | | | | | |
| Virgin LDPE 3 cycle | | 2 | 5.947 | 2.056 | 245 | 72 | 20.04 | | | | | |
| Virgin LDPE 3 cycle | | 3 | 5.948 | 2.070 | 255 | 56 | 20.71 | | | | | |
| Virgin LDPE 3 cycle | | 4 | 5.916 | 2.088 | | 60 | | | | | | |
| Virgin LDPE 3 cycle | | 5 | 5.898 | 2.118 | 255 | 72 | 20.41 | | | | | |
| Virgin LDPE 3 cycle | | 6 | 5.901 | 2.176 | 230 | 68 | 17.91 | | | | | |
| **Virgin LDPE 3 cycle** | 03/04/2003 | | | | **242** | **66.0** | **19.4** | **0.68** | **33.1** | **8.75** | **21250** | **186500** |
| Virgin LDPE 4 cycle | | 1 | 5.949 | 2.134 | 280 | 76 | 22.06 | | | | | |
| Virgin LDPE 4 cycle | | 2 | 5.968 | 2.062 | 295 | 60 | 23.97 | | | | | |
| Virgin LDPE 4 cycle | | 3 | 5.986 | 2.188 | 320 | 64 | 24.43 | | | | | |
| Virgin LDPE 4 cycle | | 4 | 5.965 | 2.126 | 270 | 68 | 21.29 | | | | | |
| Virgin LDPE 4 cycle | | 5 | 6.008 | 2.126 | 320 | 60 | 25.05 | | | | | |
| Virgin LDPE 4 cycle | | 6 | 5.959 | 1.968 | 300 | 56 | 25.58 | | | | | |
| **Virgin LDPE 4 cycle** | 07/04/2003 | | | | **298** | **64.0** | **23.7** | **0.56** | **29.8** | **8.75** | **21150** | **184000** |
| Virgin LDPE 5 cycle | | 1 | 5.939 | 2.098 | 290 | 68 | 23.27 | | | | | |
| Virgin LDPE 5 cycle | | 2 | 5.923 | 1.958 | 240 | 56 | 20.69 | | | | | |
| Virgin LDPE 5 cycle | | 3 | 5.906 | 2.005 | 260 | 56 | 21.96 | | | | | |
| Virgin LDPE 5 cycle | | 4 | 5.933 | 2.199 | 290 | 48 | 22.23 | | | | | |
| Virgin LDPE 5 cycle | | 5 | 5.948 | 2.362 | 315 | 60 | 22.42 | | | | | |
| Virgin LDPE 5 cycle | | 6 | 5.936 | 2.122 | 315 | 60 | 25.01 | | | | | |
| **Virgin LDPE 5 cycle** | 08/04/2003 | | | | **285** | **58.0** | **22.6** | **0.50** | **23.5** | **8.65** | **21450** | **185000** |
| Virgin LDPE 6 cycle | | 1 | 5.964 | 2.205 | 260 | 68 | 19.77 | | | | | |
| Virgin LDPE 6 cycle | | 2 | 6.000 | 2.232 | 310 | 56 | 23.15 | | | | | |
| Virgin LDPE 6 cycle | | 3 | 5.939 | 2.009 | 230 | 60 | 19.28 | | | | | |
| Virgin LDPE 6 cycle | | 4 | 5.940 | 2.220 | 270 | 68 | 20.48 | | | | | |
| Virgin LDPE 6 cycle | | 5 | 6.005 | 2.054 | 250 | 56 | 20.27 | | | | | |
| Virgin LDPE 6 cycle | | 6 | 5.953 | 2.186 | 260 | 72 | 19.98 | | | | | |
| **Virgin LDPE 6 cycle** | 11/04/2003 | | | | **263** | **63.3** | **20.5** | **0.45** | **28.4** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| Erema mixed PE 0 cycle | | 1 | 5.971 | 2.195 | 250 | 80 | 19.07 | | | | | |
| Erema mixed PE 0 cycle | | 2 | 5.955 | 2.167 | 225 | 68 | 17.44 | | | | | |
| Erema mixed PE 0 cycle | | 3 | 5.960 | 2.262 | 235 | 72 | 17.43 | | | | | |
| Erema mixed PE 0 cycle | | 4 | 5.992 | 2.209 | 230 | 60 | 17.38 | | | | | |
| Erema mixed PE 0 cycle | | 5 | 5.961 | 2.020 | | 120 | | | | | | |
| Erema mixed PE 0 cycle | | 6 | 5.985 | 2.186 | 240 | 64 | 18.34 | | | | | |
| **Erema mixed PE 0 cycle** | 14/04/2003 | | | | **236** | **77.3** | **17.9** | **1.05** | **34.9** | **4.2** | **22950** | **96550** |
| Erema mixed PE 1 cycle | | 1 | 5.955 | 2.301 | 260 | 60 | 18.97 | | | | | |
| Erema mixed PE 1 cycle | | 2 | 5.985 | 2.279 | | 124 | | | | | | |
| Erema mixed PE 1 cycle | | 3 | 5.973 | 2.351 | 250 | 60 | 17.80 | | | | | |
| Erema mixed PE 1 cycle | | 4 | 5.966 | 2.219 | 215 | 108 | 16.24 | | | | | |
| Erema mixed PE 1 cycle | | 5 | 5.979 | 2.314 | 235 | 92 | 16.99 | | | | | |
| Erema mixed PE 1 cycle | | 6 | 5.987 | 2.249 | 200 | 124 | 14.85 | | | | | |
| **Erema mixed PE 1 cycle** | 17/04/2003 | | | | **232** | **94.7** | **17.0** | **0.88** | **40.5** | **4.5** | **21300** | **95800** |
| Erema mixed PE 2 cycle | | 1 | 5.956 | 2.304 | 270 | 36 | 19.68 | | | | | |
| Erema mixed PE 2 cycle | | 2 | 6.017 | 2.308 | 270 | 64 | 19.44 | | | | | |
| Erema mixed PE 2 cycle | | 3 | 5.985 | 2.231 | | 88 | | | | | | |
| Erema mixed PE 2 cycle | | 4 | 6.000 | 2.335 | 240 | 68 | 17.13 | | | | | |
| Erema mixed PE 2 cycle | | 5 | 6.005 | 2.246 | 240 | 68 | 17.79 | | | | | |
| Erema mixed PE 2 cycle | | 6 | 5.984 | 2.256 | 225 | 68 | 16.67 | | | | | |
| **Erema mixed PE 2 cycle** | 23/04/2003 | | | | **249** | **65.3** | **18.1** | **0.95** | **40.3** | **4.4** | **21750** | **96550** |
| Erema mixed PE 3 cycle | | 1 | 5.975 | 2.313 | 240 | 76 | 17.37 | | | | | |
| Erema mixed PE 3 cycle | | 2 | 6.027 | 2.410 | | 64 | | | | | | |
| Erema mixed PE 3 cycle | | 3 | 6.023 | 2.325 | 270 | 92 | 19.28 | | | | | |
| Erema mixed PE 3 cycle | | 4 | 6.003 | 2.408 | 280 | 68 | 19.37 | | | | | |
| Erema mixed PE 3 cycle | | 5 | 6.022 | 2.318 | 260 | 60 | 18.63 | | | | | |
| Erema mixed PE 3 cycle | | 6 | 5.986 | 2.294 | 245 | 68 | 17.84 | | | | | |
| **Erema mixed PE 3 cycle** | 23/04/2003A | | | | **259** | **71.3** | **18.5** | **0.89** | **34.4** | **4.25** | **22550** | **95150** |
| Erema mixed PE 4 cycle | | 1 | 6.054 | 2.283 | 275 | 56 | 19.90 | | | | | |
| Erema mixed PE 4 cycle | | 2 | 6.026 | 2.225 | 240 | 64 | 17.90 | | | | | |
| Erema mixed PE 4 cycle | | 3 | 6.032 | 2.241 | 270 | 84 | 19.97 | | | | | |
| Erema mixed PE 4 cycle | | 4 | 6.024 | 2.217 | 250 | 88 | 18.72 | | | | | |
| Erema mixed PE 4 cycle | | 5 | 6.013 | 2.250 | 240 | 76 | 17.74 | | | | | |
| Erema mixed PE 4 cycle | | 6 | 6.038 | 2.363 | | 48 | | | | | | |
| **Erema mixed PE 4 cycle** | 24/04/2003 | | | | **255** | **69.3** | **18.8** | **0.87** | **30.7** | **4.55** | **20350** | **93300** |
| Erema mixed PE 5 cycle | | 1 | 6.005 | 2.180 | 265 | 48 | 20.24 | | | | | |
| Erema mixed PE 5 cycle | | 2 | 6.026 | 2.271 | 290 | 40 | 21.19 | | | | | |
| Erema mixed PE 5 cycle | | 3 | 6.033 | 2.274 | 295 | 48 | 21.50 | | | | | |
| Erema mixed PE 5 cycle | | 4 | 6.011 | 2.215 | 290 | 40 | 21.78 | | | | | |
| Erema mixed PE 5 cycle | | 5 | 6.006 | 2.202 | | 100 | | | | | | |
| Erema mixed PE 5 cycle | | 6 | 6.015 | 2.304 | 295 | 52 | 21.29 | | | | | |
| **Erema mixed PE 5 cycle** | 24/04/2003A | | | | **287** | **54.7** | **21.2** | **0.85** | **33.3** | **4.25** | **22000** | **93200** |
| Erema mixed PE 6 cycle | | 1 | 5.994 | 2.104 | 255 | 68 | 20.22 | | | | | |
| Erema mixed PE 6 cycle | | 2 | 6.016 | 2.270 | 265 | 56 | 19.40 | | | | | |
| Erema mixed PE 6 cycle | | 3 | 6.012 | 2.237 | 270 | 56 | 20.08 | | | | | |
| Erema mixed PE 6 cycle | | 4 | 6.017 | 2.188 | | 88 | | | | | | |
| Erema mixed PE 6 cycle | | 5 | 6.003 | 2.261 | 285 | 64 | 21.00 | | | | | |
| Erema mixed PE 6 cycle | | 6 | 6.016 | 2.178 | 250 | 60 | 19.08 | | | | | |
| **Erema mixed PE 6 cycle** | 28/04/2003 | | | | **265** | **65.3** | **20.0** | **0.85** | **36.9** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| Erema mixed PE 7 cycle | | 1 | 5.997 | 2.084 | 230 | 68 | 18.40 | | | | | |
| Erema mixed PE 7 cycle | | 2 | 6.013 | 2.264 | 255 | 84 | 18.73 | | | | | |
| Erema mixed PE 7 cycle | | 3 | 6.023 | 2.244 | 260 | 52 | 19.24 | | | | | |
| Erema mixed PE 7 cycle | | 4 | 5.989 | 2.203 | 290 | 40 | 21.98 | | | | | |
| Erema mixed PE 7 cycle | | 5 | 6.009 | 2.259 | 270 | 44 | 19.89 | | | | | |
| Erema mixed PE 7 cycle | | 6 | 6.011 | 2.294 | | 40 | | | | | | |
| **Erema mixed PE 7 cycle** | 28/04/2003A | | | | **261** | **54.7** | **19.6** | **0.85** | **36.8** | | | |
| Erema mixed PE 8 cycle | | 1 | 6.038 | 2.292 | 285 | 40 | 20.59 | | | | | |
| Erema mixed PE 8 cycle | | 2 | 5.971 | 2.097 | | | | | | | | |
| Erema mixed PE 8 cycle | | 3 | 6.010 | 2.219 | 270 | 100 | 20.25 | | | | | |
| Erema mixed PE 8 cycle | | 4 | 6.019 | 2.203 | 230 | 84 | 17.35 | | | | | |
| Erema mixed PE 8 cycle | | 5 | 6.016 | 2.346 | 320 | 40 | 22.67 | | | | | |
| Erema mixed PE 8 cycle | | 6 | 6.002 | 2.224 | 260 | 44 | 19.48 | | | | | |
| **Erema mixed PE 8 cycle** | 28/04/2003B | | | | **273** | **61.6** | **20.1** | **0.85** | **37.6** | | | |
| cbags +0 cycles | | 1 | 6.015 | 2.146 | 460 | 28 | 35.64 | | | | | |
| cbags +0 cycles | | 2 | 6.006 | 2.315 | 450 | 20 | 32.37 | | | | | |
| cbags +0 cycles | | 3 | 5.994 | 2.290 | 515 | 24 | 37.52 | | | | | |
| cbags +0 cycles | | 4 | 6.017 | 2.262 | 475 | 24 | 34.90 | | | | | |
| cbags +0 cycles | | 5 | 6.037 | 2.340 | 700 | 24 | 49.55 | | | | | |
| cbags +0 cycles | | 6 | 6.023 | 2.212 | 510 | 28 | 38.28 | | | | | |
| **cbags +0 cycles** | 02/05/2003 | | | | **518** | **24.7** | **38.0** | **0.08** | **77.3** | | | |
| cbags +1 cycles | | 1 | 6.036 | 2.133 | 650 | 20 | 50.49 | | | | | |
| cbags +1 cycles | | 2 | 6.026 | 2.127 | 600 | 24 | 46.81 | | | | | |
| cbags +1 cycles | | 3 | 6.014 | 2.255 | 675 | 24 | 49.77 | | | | | |
| cbags +1 cycles | | 4 | 6.029 | 2.203 | 580 | 20 | 43.67 | | | | | |
| cbags +1 cycles | | 5 | 6.016 | 2.292 | 600 | 28 | 43.51 | | | | | |
| cbags +1 cycles | | 6 | 6.023 | 2.241 | 675 | 28 | 50.01 | | | | | |
| **cbags +1 cycles** | 06/05/2003 | | | | **630** | **24.0** | **47.4** | **0.12** | **75.6** | **13.5** | **12450** | **170000** |
| cbags +2 cycles | | 1 | 6.012 | 2.061 | 600 | 24 | 48.42 | | | | | |
| cbags +2 cycles | | 2 | 6.013 | 2.074 | 540 | 20 | 43.30 | | | | | |
| cbags +2 cycles | | 3 | 6.018 | 2.108 | 610 | 24 | 48.08 | | | | | |
| cbags +2 cycles | | 4 | 6.007 | 2.063 | 550 | 24 | 44.38 | | | | | |
| cbags +2 cycles | | 5 | 6.016 | 2.105 | 675 | 24 | 53.30 | | | | | |
| cbags +2 cycles | | 6 | 6.023 | 2.263 | 700 | 20 | 51.36 | | | | | |
| **cbags +2 cycles** | 08/05/2003 | | | | **613** | **22.7** | **48.1** | **0.13** | **74.7** | **15** | **11450** | **172500** |
| cbags +3 cycles | | 1 | 6.015 | 2.079 | 600 | 24 | 47.98 | | | | | |
| cbags +3 cycles | | 2 | 6.012 | 2.094 | 620 | 24 | 49.25 | | | | | |
| cbags +3 cycles | | 3 | 6.020 | 2.027 | 550 | 24 | 45.07 | | | | | |
| cbags +3 cycles | | 4 | 6.023 | 2.081 | 570 | 20 | 45.48 | | | | | |
| cbags +3 cycles | | 5 | 6.003 | 2.093 | 600 | 24 | 47.75 | | | | | |
| cbags +3 cycles | | 6 | 6.029 | 2.078 | 590 | 24 | 47.09 | | | | | |
| **cbags +3 cycles** | 16/05/2003 | | | | **588** | **23.3** | **47.1** | **0.14** | **73.6** | **17** | **10550** | **179500** |
| cbags +4 cycles | | 1 | 6.005 | 2.131 | 670 | 24 | 52.36 | | | | | |
| cbags +4 cycles | | 2 | 6.009 | 2.110 | 650 | 24 | 51.27 | | | | | |
| cbags +4 cycles | | 3 | 6.006 | 2.051 | 600 | 20 | 48.71 | | | | | |
| cbags +4 cycles | | 4 | 6.011 | 2.156 | 680 | 24 | 52.47 | | | | | |
| cbags +4 cycles | | 5 | 6.012 | 2.135 | 700 | 24 | 54.54 | | | | | |
| cbags +4 cycles | | 6 | 6.015 | 2.125 | 650 | 24 | 50.85 | | | | | |
| **cbags +4 cycles** | 19/05/2003 | | | | **658** | **23.3** | **51.7** | **0.16** | **73.6** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| cbags +5 cycles | | 1 | 6.017 | 2.091 | 610 | 24 | 48.48 | | | | | |
| cbags +5 cycles | | 2 | 6.013 | 2.107 | 620 | 20 | 48.94 | | | | | |
| cbags +5 cycles | | 3 | 6.009 | 2.138 | 620 | 24 | 48.26 | | | | | |
| cbags +5 cycles | | 4 | 6.014 | 2.141 | 600 | 24 | 46.60 | | | | | |
| cbags +5 cycles | | 5 | 6.013 | 2.133 | 570 | 20 | 44.44 | | | | | |
| cbags +5 cycles | | 6 | 6.009 | 2.105 | 620 | 24 | 49.02 | | | | | |
| **cbags +5 cycles** | 19/05/2003A | | | | **607** | **22.7** | **47.6** | **0.16** | **70.1** | | | |
| cbags +6 cycles | | 1 | 6.015 | 2.090 | 580 | 24 | 46.14 | | | | | |
| cbags +6 cycles | | 2 | 6.014 | 2.062 | 500 | 20 | 40.32 | | | | | |
| cbags +6 cycles | | 3 | 6.021 | 2.109 | 580 | 20 | 45.68 | | | | | |
| cbags +6 cycles | | 4 | 6.012 | 2.138 | 590 | 24 | 45.90 | | | | | |
| cbags +6 cycles | | | | | | | | | | | | |
| cbags +6 cycles | | 6 | 6.011 | 2.080 | 530 | 24 | 42.39 | | | | | |
| **cbags +6 cycles** | 20/05/2003 | | | | **556** | **22.4** | **44.1** | **0.17** | **70.6** | | | |
| cbags +7 cycles | | 1 | 6.005 | 2.023 | 530 | 20 | 43.63 | | | | | |
| cbags +7 cycles | | 2 | 6.010 | 2.080 | 550 | 20 | 44.00 | | | | | |
| cbags +7 cycles | | 3 | 6.021 | 2.116 | 600 | 20 | 47.09 | | | | | |
| cbags +7 cycles | | 4 | 6.009 | 2.054 | 570 | 24 | 46.18 | | | | | |
| cbags +7 cycles | | 5 | 6.014 | 2.109 | 570 | 20 | 44.94 | | | | | |
| cbags +7 cycles | | 6 | 6.011 | 2.175 | 640 | 24 | 48.95 | | | | | |
| **cbags +7 cycles** | 20/05/2003A | | | | **577** | **21.3** | **45.8** | **0.17** | **75.7** | | | |
| smarket LDPE 0 cycle | | 1 | 6.008 | 2.207 | 370 | 40 | 27.90 | | | | | |
| smarket LDPE 0 cycle | | 2 | 5.955 | 2.058 | 360 | 32 | 29.37 | | | | | |
| smarket LDPE 0 cycle | | 3 | 5.973 | 2.062 | 370 | 36 | 30.04 | | | | | |
| smarket LDPE 0 cycle | | 4 | 5.938 | 2.124 | 400 | 32 | 31.72 | | | | | |
| smarket LDPE 0 cycle | | 5 | 5.967 | 2.032 | 385 | 40 | 31.75 | | | | | |
| smarket LDPE 0 cycle | | 6 | 5.957 | 2.121 | 490 | 40 | 38.78 | | | | | |
| **smarket LDPE 0 cycle** | 28/05/2003 | | | | **396** | **36.7** | **31.6** | **0.52** | **44.6** | | | |
| smarket LDPE 1 cycle | | 1 | 5.980 | 2.169 | 350 | 36 | 26.98 | | | | | |
| smarket LDPE 1 cycle | | 2 | 5.955 | 2.016 | 360 | 40 | 29.99 | | | | | |
| smarket LDPE 1 cycle | | 3 | 5.974 | 2.131 | 430 | 36 | 33.78 | | | | | |
| smarket LDPE 1 cycle | | 4 | 5.977 | 2.140 | 340 | 36 | 26.58 | | | | | |
| smarket LDPE 1 cycle | | 5 | 5.965 | 2.150 | 320 | 40 | 24.95 | | | | | |
| smarket LDPE 1 cycle | | 6 | 5.977 | 2.188 | 380 | 32 | 29.06 | | | | | |
| **smarket LDPE 1 cycle** | 02/06/2003 | | | | **363** | **36.7** | **28.6** | **0.41** | **41.3** | | | |
| smarket LDPE 2 cycle | | 1 | 5.963 | 2.146 | 390 | 24 | 30.48 | | | | | |
| smarket LDPE 2 cycle | | 2 | 5.970 | 1.962 | 310 | 36 | 26.47 | | | | | |
| smarket LDPE 2 cycle | | 3 | 5.952 | 2.029 | 355 | 28 | 29.40 | | | | | |
| smarket LDPE 2 cycle | | 4 | 5.974 | 1.988 | 370 | 44 | 31.15 | | | | | |
| smarket LDPE 2 cycle | | 5 | 5.939 | 1.971 | 310 | 32 | 26.48 | | | | | |
| smarket LDPE 2 cycle | | 6 | 5.952 | 2.106 | 390 | 28 | 31.11 | | | | | |
| **smarket LDPE 2 cycle** | 03/06/2003 | | | | **354** | **32.0** | **29.2** | **0.40** | **46.6** | | | |
| smarket LDPE 3 cycle | | 1 | 5.997 | 1.931 | 375 | 44 | 32.38 | | | | | |
| smarket LDPE 3 cycle | | 2 | 5.968 | 1.993 | 360 | 44 | 30.27 | | | | | |
| smarket LDPE 3 cycle | | 3 | 5.956 | 2.006 | 375 | 28 | 31.39 | | | | | |
| smarket LDPE 3 cycle | | 4 | 5.964 | 1.988 | 330 | 32 | 27.83 | | | | | |
| smarket LDPE 3 cycle | | 5 | 5.975 | 2.073 | 360 | 32 | 29.06 | | | | | |
| smarket LDPE 3 cycle | | 6 | 5.980 | 2.052 | 420 | 24 | 34.23 | | | | | |
| **smarket LDPE 3 cycle** | 04/06/2003 | | | | **370** | **34.0** | **30.9** | **0.33** | **50.1** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| smarket LDPE 4 cycle | | 1 | 5.944 | 1.966 | 340 | 36 | 29.09 | | | | | |
| smarket LDPE 4 cycle | | 2 | 5.947 | 2.035 | 400 | 16 | 33.05 | | | | | |
| smarket LDPE 4 cycle | | 3 | 5.942 | 2.025 | 350 | 28 | 29.09 | | | | | |
| smarket LDPE 4 cycle | | 4 | 5.965 | 2.000 | 420 | 40 | 35.21 | | | | | |
| smarket LDPE 4 cycle | | 5 | 5.963 | 2.072 | 450 | 20 | 36.42 | | | | | |
| smarket LDPE 4 cycle | | 6 | 5.935 | 2.040 | 350 | 28 | 28.91 | | | | | |
| **smarket LDPE 4 cycle** | 04/06/2003A | | | | **385** | **28.0** | **32.0** | **0.29** | **51.1** | | | |
| smarket LDPE 5 cycle | | 1 | 5.982 | 2.022 | 460 | 12 | 38.03 | | | | | |
| smarket LDPE 5 cycle | | 2 | 5.944 | 1.960 | 370 | 32 | 31.76 | | | | | |
| smarket LDPE 5 cycle | | 3 | 5.951 | 1.970 | 390 | 24 | 33.27 | | | | | |
| smarket LDPE 5 cycle | | 4 | 5.971 | 2.050 | 490 | 12 | 40.03 | | | | | |
| smarket LDPE 5 cycle | | 5 | 5.993 | 2.160 | 580 | 4 | 44.81 | | | | | |
| smarket LDPE 5 cycle | | 6 | 5.956 | 2.073 | 420 | 28 | 34.02 | | | | | |
| **smarket LDPE 5 cycle** | 05/06/2003 | | | | **452** | **18.7** | **37.0** | **0.28** | **47** | | | |
| smarket LDPE 6 cycle | | 1 | 5.995 | 2.083 | 360 | 32 | 28.83 | | | | | |
| smarket LDPE 6 cycle | | 2 | 5.945 | 2.105 | 440 | 32 | 35.16 | | | | | |
| smarket LDPE 6 cycle | | 3 | 5.956 | 2.005 | 425 | 16 | 35.59 | | | | | |
| smarket LDPE 6 cycle | | 4 | 5.954 | 2.034 | 410 | 16 | 33.86 | | | | | |
| smarket LDPE 6 cycle | | 5 | 5.979 | 2.036 | 400 | 16 | 32.86 | | | | | |
| smarket LDPE 6 cycle | | 6 | 5.954 | 2.023 | 450 | 12 | 37.36 | | | | | |
| **smarket LDPE 6 cycle** | 05/06/2003A | | | | **414** | **20.7** | **33.9** | **0.28** | **52.8** | | | |
| smarket LDPE 7 cycle | | 1 | 6.008 | 2.194 | 560 | 16 | 42.48 | | | | | |
| smarket LDPE 7 cycle | | 2 | 5.948 | 1.978 | 440 | 12 | 37.40 | | | | | |
| smarket LDPE 7 cycle | | 3 | 5.947 | 2.061 | 400 | 24 | 32.64 | | | | | |
| smarket LDPE 7 cycle | | 4 | 5.943 | 1.956 | 370 | 24 | 31.83 | | | | | |
| smarket LDPE 7 cycle | | 5 | 5.951 | 2.048 | 370 | 28 | 30.36 | | | | | |
| smarket LDPE 7 cycle | | 6 | 5.961 | 2.000 | 400 | 32 | 33.55 | | | | | |
| **smarket LDPE 7 cycle** | 05/06/2003B | | | | **423** | **22.7** | **34.7** | **0.27** | **45.8** | | | |
| virgin plus 5% cling film | | 1 | 5.979 | 1.899 | 240 | 88 | 21.14 | | | | | |
| virgin plus 5% cling film | | 2 | 5.936 | 1.964 | 200 | 88 | 17.16 | | | | | |
| virgin plus 5% cling film | | 3 | 5.963 | 1.990 | 210 | 80 | 17.70 | | | | | |
| virgin plus 5% cling film | | 4 | 5.970 | 1.907 | 230 | 80 | 20.20 | | | | | |
| virgin plus 5% cling film | | 5 | 5.915 | 1.998 | 210 | 80 | 17.77 | | | | | |
| virgin plus 5% cling film | | 6 | 5.962 | 2.013 | 230 | 76 | 19.16 | | | | | |
| **virgin plus 5% LLDPE** | 12/08/2003A | | | | **220** | **82.0** | **18.9** | **1.26** | **28.1** | | | |
| virgin plus 10% LLDPE | | 1 | 5.979 | 2.092 | 230 | 88 | 18.39 | | | | | |
| virgin plus 10% LLDPE | | 2 | 5.983 | 2.059 | 230 | 80 | 18.67 | | | | | |
| virgin plus 10% LLDPE | | 3 | 5.986 | 2.243 | 230 | 96 | 17.13 | | | | | |
| virgin plus 10% LLDPE | | | | | | | | | | | | |
| virgin plus 10% LLDPE | | 5 | 5.973 | 1.999 | 240 | 92 | 20.10 | | | | | |
| virgin plus 10% LLDPE | | 6 | 5.991 | 2.051 | 200 | 84 | 16.28 | | | | | |
| **virgin plus 10% LLDPE** | 28/08/2003 | | | | **226** | **88.0** | **18.1** | **1.46** | **27.6** | | | |
| virgin plus 15% LLDPE | | 1 | 5.976 | 1.957 | 260 | 60 | 22.23 | | | | | |
| virgin plus 15% LLDPE | | 2 | 5.977 | 1.952 | 265 | 68 | 22.71 | | | | | |
| virgin plus 15% LLDPE | | 3 | 5.977 | 2.023 | 260 | 64 | 21.50 | | | | | |
| virgin plus 15% LLDPE | | 4 | 5.971 | 2.026 | 240 | 76 | 19.84 | | | | | |
| virgin plus 15% LLDPE | | 5 | 5.971 | 2.069 | 230 | 72 | 18.62 | | | | | |
| virgin plus 15% LLDPE | | | | | | | | | | | | |
| **virgin plus 15% LLDPE** | 28/08/2003A | | | | **251** | **68.0** | **21.0** | **1.16** | **33.9** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| virgin plus 20% LLDPE | | 1 | 5.965 | 2.073 | 200 | 96 | 16.17 | | | | | |
| virgin plus 20% LLDPE | | 2 | 5.984 | 2.059 | 220 | 80 | 17.86 | | | | | |
| virgin plus 20% LLDPE | | 3 | 5.970 | 2.057 | 225 | 88 | 18.32 | | | | | |
| virgin plus 20% LLDPE | | 4 | 5.988 | 2.131 | 240 | 96 | 18.81 | | | | | |
| virgin plus 20% LLDPE | | 5 | 5.947 | 2.124 | 215 | 68 | 17.02 | | | | | |
| virgin plus 20% LLDPE | | | | | | | | | | | | |
| **virgin plus 20% LLDPE** | 28/08/2003B | | | | **220** | **85.6** | **17.6** | **1.17** | **26.5** | | | |
| 100% LLDPE | | 1 | 5.992 | 2.132 | 320 | 48 | 25.05 | | | | | |
| 100% LLDPE | | 2 | 5.991 | 2.046 | 320 | 44 | 26.11 | | | | | |
| 100% LLDPE | | 3 | 5.926 | 1.959 | 250 | 40 | 21.53 | | | | | |
| 100% LLDPE | | 4 | 5.960 | 2.019 | 275 | 40 | 22.85 | | | | | |
| 100% LLDPE | | 5 | 5.944 | 1.944 | 230 | 40 | 19.90 | | | | | |
| 100% LLDPE | | 6 | 5.977 | 2.079 | 250 | 44 | 20.12 | | | | | |
| **100% LLDPE** | 12/08/2003 | | | | **274** | **42.7** | **22.6** | **1.14** | **34** | | | |
| Erema plus 5% LLDPE | | 1 | 6.005 | 2.072 | 230 | 52 | 18.49 | | | | | |
| Erema plus 5% LLDPE | | 2 | 5.941 | 1.910 | 220 | 108 | 19.39 | | | | | |
| Erema plus 5% LLDPE | | 3 | 5.978 | 2.139 | 235 | 108 | 18.38 | | | | | |
| Erema plus 5% LLDPE | | 4 | 5.982 | 2.076 | 270 | 52 | 21.74 | | | | | |
| Erema plus 5% LLDPE | | 5 | 5.969 | 2.046 | 230 | 60 | 18.83 | | | | | |
| Erema plus 5% LLDPE | | | | | | | | | | | | |
| **Erema plus 5% LLDPE** | 08/09/2003 | | | | **237** | **76.0** | **19.4** | **1.02** | **34.1** | | | |
| Erema plus 10% LLDPE | | 1 | 5.983 | 2.108 | 275 | 40 | 21.80 | | | | | |
| Erema plus 10% LLDPE | | | | | | | | | | | | |
| Erema plus 10% LLDPE | | 3 | 5.990 | 2.185 | 250 | 40 | 19.10 | | | | | |
| Erema plus 10% LLDPE | | 4 | 5.984 | 2.077 | 235 | 40 | 18.91 | | | | | |
| Erema plus 10% LLDPE | | 5 | 5.961 | 2.085 | 235 | 40 | 18.91 | | | | | |
| Erema plus 10% LLDPE | | 6 | 5.958 | 2.074 | 245 | 52 | 19.83 | | | | | |
| **Erema plus 10% LLDPE** | 15/09/2003 | | | | **248** | **42.4** | **19.7** | **1.06** | **41.2** | | | |
| Erema plus 15% LLDPE | | 1 | 5.945 | 2.025 | 230 | 108 | 19.11 | | | | | |
| Erema plus 15% LLDPE | | 2 | 5.996 | 2.050 | 265 | 80 | 21.56 | | | | | |
| Erema plus 15% LLDPE | | 3 | 5.976 | 2.014 | 260 | 60 | 21.60 | | | | | |
| Erema plus 15% LLDPE | | | | | | | | | | | | |
| Erema plus 15% LLDPE | | 5 | 5.985 | 2.020 | 230 | 72 | 19.02 | | | | | |
| Erema plus 15% LLDPE | | 6 | 5.989 | 2.145 | 240 | 60 | 18.68 | | | | | |
| **Erema plus 15% LLDPE** | 15/09/2003A | | | | **245** | **76.0** | **20.0** | **1.06** | **31.2** | | | |
| Erema plus 20% LLDPE | | 1 | 5.992 | 2.045 | 260 | 60 | 21.22 | | | | | |
| Erema plus 20% LLDPE | | | | | | | | | | | | |
| Erema plus 20% LLDPE | | 3 | 5.968 | 1.993 | 240 | 84 | 20.18 | | | | | |
| Erema plus 20% LLDPE | | 4 | 5.994 | 2.137 | 240 | 44 | 18.74 | | | | | |
| Erema plus 20% LLDPE | | 5 | 6.002 | 2.145 | 260 | 68 | 20.20 | | | | | |
| Erema plus 20% LLDPE | | 6 | 5.998 | 2.177 | 240 | 40 | 18.38 | | | | | |
| **Erema plus 20% LLDPE** | 17/09/2003 | | | | **248** | **59.2** | **19.7** | **1.01** | **35.1** | | | |
| Erema plus 25% LLDPE | | | | | | | | | | | | |
| Erema plus 25% LLDPE | | 2 | 5.957 | 1.916 | 180 | 76 | 15.77 | | | | | |
| Erema plus 25% LLDPE | | 3 | 5.943 | 1.944 | 175 | 72 | 15.15 | | | | | |
| Erema plus 25% LLDPE | | 4 | 5.999 | 1.953 | 215 | 68 | 18.35 | | | | | |
| Erema plus 25% LLDPE | | 5 | 5.973 | 2.148 | 220 | 60 | 17.15 | | | | | |
| Erema plus 25% LLDPE | | 6 | 5.952 | 1.973 | 210 | 68 | 17.88 | | | | | |
| **Erema plus 25% LLDPE** | 17/09/2003B | | | | **200** | **68.8** | **16.9** | **1.05** | **34.3** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| Erema plus 30% LLDPE | | 1 | 5.944 | 1.982 | 190 | 68 | 16.13 | | | | | |
| Erema plus 30% LLDPE | | 2 | 5.973 | 2.040 | 225 | 68 | 18.46 | | | | | |
| Erema plus 30% LLDPE | | 3 | 5.994 | 2.052 | 245 | 80 | 19.92 | | | | | |
| Erema plus 30% LLDPE | | 4 | 5.989 | 2.086 | 210 | 60 | 16.81 | | | | | |
| Erema plus 30% LLDPE | | 5 | 5.990 | 1.979 | 240 | 60 | 20.24 | | | | | |
| Erema plus 30% LLDPE | | | | | | | | | | | | |
| **Erema plus 30% LLDPE** | 19/09/2003 | | | | **222** | **67.2** | **18.3** | **1.06** | **29.4** | | | |
| Erema plus 50% LLDPE | | 1 | 5.990 | 2.131 | 240 | 60 | 18.80 | | | | | |
| Erema plus 50% LLDPE | | | | | | | | | | | | |
| Erema plus 50% LLDPE | | 3 | 5.954 | 1.936 | 200 | 72 | 17.35 | | | | | |
| Erema plus 50% LLDPE | | 4 | 5.954 | 1.978 | 225 | 64 | 19.11 | | | | | |
| Erema plus 50% LLDPE | | 5 | 5.968 | 2.001 | 250 | 52 | 20.94 | | | | | |
| Erema plus 50% LLDPE | | 6 | 5.978 | 1.974 | 210 | 80 | 17.80 | | | | | |
| **Erema plus 50% LLDPE** | 24/09/2003 | | | | **225** | **65.6** | **18.8** | **1.08** | **27.2** | | | |
| Erema plus 75% LLDPE | | | | | | | | | | | | |
| Erema plus 75% LLDPE | | 2 | 5.940 | 1.932 | 180 | 80 | 15.69 | | | | | |
| Erema plus 75% LLDPE | | 3 | 5.953 | 2.137 | 240 | 68 | 18.87 | | | | | |
| Erema plus 75% LLDPE | | 4 | 5.937 | 1.923 | 225 | 120 | 19.70 | | | | | |
| Erema plus 75% LLDPE | | 5 | 5.954 | 1.951 | 225 | 104 | 19.38 | | | | | |
| Erema plus 75% LLDPE | | | | | | | | | | | | |
| **Erema plus 75% LLDPE** | 26/09/2003 | | | | **218** | **93.0** | **18.4** | **1.08** | **31.5** | | | |
| 100% LLDPE | | 1 | 5.992 | 2.132 | 320 | 48 | 25.05 | | | | | |
| 100% LLDPE | | 2 | 5.991 | 2.046 | 320 | 44 | 26.11 | | | | | |
| 100% LLDPE | | 3 | 5.926 | 1.959 | 250 | 40 | 21.53 | | | | | |
| 100% LLDPE | | 4 | 5.960 | 2.019 | 275 | 40 | 22.85 | | | | | |
| 100% LLDPE | | 5 | 5.944 | 1.944 | 230 | 40 | 19.90 | | | | | |
| 100% LLDPE | | 6 | 5.977 | 2.079 | 250 | 44 | 20.12 | | | | | |
| **100% LLDPE** | 12/08/2003 | | | | **274** | **42.7** | **22.6** | **1.14** | **34** | | | |
| Virgin LD 5% talc | | 1 | 5.957 | 2.177 | 240 | 84 | 18.51 | | | | | |
| Virgin LD 5% talc | | 2 | 5.946 | 2.121 | 240 | 60 | 19.03 | | | | | |
| Virgin LD 5% talc | | 3 | 5.963 | 2.079 | 220 | 84 | 17.75 | | | | | |
| Virgin LD 5% talc | | 4 | 5.985 | 2.004 | 220 | 68 | 18.34 | | | | | |
| Virgin LD 5% talc | | 5 | 5.945 | 2.166 | 225 | 76 | 17.47 | | | | | |
| Virgin LD 5% talc | | 6 | 5.982 | 1.924 | 275 | 76 | 23.89 | | | | | |
| **Virgin LD 5% talc** | 23/07/2003 | | | | **237** | **74.7** | **19.2** | **1.51** | **41.8** | | | |
| Virgin LD 10% talc | | 1 | 5.989 | 1.949 | 230 | 40 | 19.70 | | | | | |
| Virgin LD 10% talc | | 2 | 5.970 | 2.062 | 225 | 40 | 18.28 | | | | | |
| Virgin LD 10% talc | | 3 | 5.970 | 2.111 | 255 | 28 | 20.23 | | | | | |
| Virgin LD 10% talc | | 4 | 5.963 | 2.002 | 210 | 36 | 17.59 | | | | | |
| Virgin LD 10% talc | | 5 | 5.972 | 2.117 | 235 | 48 | 18.59 | | | | | |
| Virgin LD 10% talc | | 6 | 5.968 | 2.176 | 260 | 64 | 20.02 | | | | | |
| **Virgin LD 10% talc** | 23/07/2003A | | | | **236** | **42.7** | **19.1** | **1.28** | **48.9** | | | |
| Virgin LD 15% talc | | 1 | 5.925 | 1.870 | 165 | 52 | 14.89 | | | | | |
| Virgin LD 15% talc | | 2 | 5.956 | 2.100 | 225 | 40 | 17.99 | | | | | |
| Virgin LD 15% talc | | 3 | 5.979 | 2.187 | 185 | 36 | 14.15 | | | | | |
| Virgin LD 15% talc | | 4 | 5.988 | 1.999 | 275 | 32 | 22.97 | | | | | |
| Virgin LD 15% talc | | 5 | 5.989 | 1.973 | 275 | 36 | 23.27 | | | | | |
| Virgin LD 15% talc | | 6 | 5.986 | 2.009 | 250 | 44 | 20.79 | | | | | |
| **Virgin LD 15% talc** | 24/07/2003 | | | | **229** | **40.0** | **19.0** | **1.30** | **45.1** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| Erema mix 5% talc | | 1 | 6.014 | 2.060 | 265 | 48 | 21.39 | | | | | |
| Erema mix 5% talc | | 2 | 6.005 | 2.095 | 260 | 52 | 20.67 | | | | | |
| Erema mix 5% talc | | 3 | 6.008 | 2.105 | 310 | 40 | 24.51 | | | | | |
| Erema mix 5% talc | | 4 | 6.021 | 2.123 | 325 | 40 | 25.43 | | | | | |
| Erema mix 5% talc | | 5 | 6.003 | 2.086 | 305 | 40 | 24.36 | | | | | |
| Erema mix 5% talc | | 6 | 6.013 | 2.135 | 305 | 40 | 23.76 | | | | | |
| **Erema mix 5% talc** | 24/07/2003A | | | | **295** | **43.3** | **23.4** | **0.92** | **49.8** | | | |
| Erema mix 10% talc | | 1 | 6.009 | 2.173 | 325 | 24 | 24.89 | | | | | |
| Erema mix 10% talc | | 2 | 5.996 | 2.109 | 280 | 32 | 22.14 | | | | | |
| Erema mix 10% talc | | 3 | 5.984 | 2.160 | 350 | 20 | 27.08 | | | | | |
| Erema mix 10% talc | | 4 | 5.978 | 2.012 | 265 | 32 | 22.03 | | | | | |
| Erema mix 10% talc | | 5 | 5.997 | 2.091 | 290 | 40 | 23.13 | | | | | |
| Erema mix 10% talc | | 6 | 6.011 | 2.317 | 335 | 28 | 24.05 | | | | | |
| **Erema mix 10% talc** | 24/07/2003B | | | | **308** | **29.3** | **23.9** | **0.90** | **44.8** | | | |
| Erema mix 15% talc | | 1 | 5.981 | 2.053 | 225 | 40 | 18.32 | | | | | |
| Erema mix 15% talc | | 2 | 5.960 | 2.024 | 240 | 24 | 19.90 | | | | | |
| Erema mix 15% talc | | 3 | 5.973 | 2.033 | 220 | 60 | 18.12 | | | | | |
| Erema mix 15% talc | | | | | | | | | | | | |
| Erema mix 15% talc | | 5 | 6.002 | 2.189 | 240 | 20 | 18.27 | | | | | |
| Erema mix 15% talc | | 6 | 6.005 | 2.109 | 300 | 16 | 23.69 | | | | | |
| **Erema mix 15% talc** | 25/07/2003 | | | | **245** | **32.0** | **19.7** | **0.90** | **51.2** | | | |
| Erema plus 1% PP tape | | 1 | 1.982 | 5.962 | 205 | 72 | 17.35 | | | | | |
| Erema plus 1% PP tape | | 2 | 2.201 | 5.251 | 250 | 64 | 21.64 | | | | | |
| Erema plus 1% PP tape | | 3 | 2.118 | 5.966 | 230 | 52 | 18.20 | | | | | |
| Erema plus 1% PP tape | | 4 | 2.187 | 5.996 | 250 | 52 | 19.07 | | | | | |
| Erema plus 1% PP tape | | 5 | 2.002 | 5.990 | 230 | 40 | 19.18 | | | | | |
| Erema plus 1% PP tape | | 6 | 2.224 | 5.961 | 235 | 52 | 17.72 | | | | | |
| **Erema plus 1% PP tape** | 30/09/2003 | | | | **233** | **55.3** | **18.9** | **0.95** | **35** | **4** | **24500** | **97400** |
| Erema plus 2% PP tape | | 1 | 2.133 | 5.967 | 200 | 100 | 15.71 | | | | | |
| Erema plus 2% PP tape | | 2 | 2.214 | 5.985 | 220 | 60 | 16.61 | | | | | |
| Erema plus 2% PP tape | | 3 | 2.053 | 5.987 | 215 | 60 | 17.50 | | | | | |
| Erema plus 2% PP tape | | 4 | 2.020 | 5.961 | 220 | 44 | 18.27 | | | | | |
| Erema plus 2% PP tape | | 5 | 2.237 | 6.002 | 240 | 52 | 17.88 | | | | | |
| Erema plus 2% PP tape | | 6 | 2.168 | 5.975 | 225 | 44 | 17.37 | | | | | |
| **Erema plus 2% PP tape** | 30/09/2003A | | | | **220** | **60.0** | **17.2** | **0.93** | **30.2** | **3.9** | **24650** | **95050** |
| Erema plus 4% PP tape | | 1 | 2.066 | 6.000 | 275 | 40 | 22.19 | | | | | |
| Erema plus 4% PP tape | | 2 | 1.922 | 5.994 | 170 | 80 | 14.76 | | | | | |
| Erema plus 4% PP tape | | 3 | 2.006 | 5.983 | 225 | 52 | 18.74 | | | | | |
| Erema plus 4% PP tape | | 4 | 2.170 | 5.980 | 250 | 52 | 19.27 | | | | | |
| Erema plus 4% PP tape | | 5 | 2.185 | 5.991 | 270 | 40 | 20.63 | | | | | |
| Erema plus 4% PP tape | | 6 | 2.064 | 5.992 | 240 | 56 | 19.40 | | | | | |
| **Erema plus 4% PP tape** | 01/10/2003 | | | | **238** | **53.3** | **19.2** | **1.16** | **34.9** | **3.9** | **24750** | **95800** |
| Erema plus 6% PP tape | | 1 | 2.080 | 6.006 | 235 | 56 | 18.81 | | | | | |
| Erema plus 6% PP tape | | | | | | | | | | | | |
| Erema plus 6% PP tape | | 3 | 2.147 | 6.002 | 220 | 48 | 17.08 | | | | | |
| Erema plus 6% PP tape | | | | | | | | | | | | |
| Erema plus 6% PP tape | | 5 | 2.133 | 6.008 | 230 | 36 | 17.95 | | | | | |
| Erema plus 6% PP tape | | 6 | 2.019 | 5.979 | 180 | 56 | 14.91 | | | | | |
| **Erema plus 6% PP tape** | 01/10/2003A | | | | ***216*** | ***49.0*** | ***17.2*** | ***1.16*** | **36.7** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| ldpe2 plus 0% cellotape | | 1 | 5.947 | 1.977 | 355 | 48 | 30.20 | | | | | |
| ldpe2 plus 0% cellotape | | 2 | 5.997 | 2.196 | 450 | 44 | 34.17 | | | | | |
| ldpe2 plus 0% cellotape | | 3 | 5.965 | 1.981 | 340 | 39 | 28.78 | | | | | |
| ldpe2 plus 0% cellotape | | 4 | 6.003 | 1.922 | 340 | 39 | 29.47 | | | | | |
| ldpe2 plus 0% cellotape | | 5 | 5.985 | 2.120 | 320 | 40 | 25.22 | | | | | |
| ldpe2 plus 0% cellotape | | 6 | 5.980 | 2.083 | 365 | 56 | 29.30 | | | | | |
| **ldpe2 plus 0% cellotape** | 03/10/2003A | | | | **362** | **44.3** | **29.5** | **0.45** | | | | |
| ldpe2 plus 2% cellotape | | 1 | 2.133 | 5.964 | 340 | 40 | 26.73 | | | | | |
| ldpe2 plus 2% cellotape | | 2 | 2.109 | 5.998 | 300 | 32 | 23.71 | | | | | |
| ldpe2 plus 2% cellotape | | 3 | 2.233 | 5.968 | 290 | 40 | 21.76 | | | | | |
| ldpe2 plus 2% cellotape | | 4 | 2.186 | 5.978 | 380 | 48 | 29.08 | | | | | |
| ldpe2 plus 2% cellotape | | 5 | 2.094 | 5.960 | 330 | 36 | 26.44 | | | | | |
| ldpe2 plus 2% cellotape | | 6 | 2.138 | 5.975 | 340 | 40 | 26.62 | | | | | |
| **ldpe2 plus 2% cellotape** | 29/04/2004 | | | | **330** | **39.3** | **25.7** | **0.40** | | | | |
| ldpe2 plus 4% cellotape | | 1 | 2.102 | 6.000 | 190 | 20 | 15.07 | | | | | |
| ldpe2 plus 4% cellotape | | 2 | 2.075 | 5.983 | 190 | 32 | 15.31 | | | | | |
| ldpe2 plus 4% cellotape | | 3 | 2.144 | 5.998 | 270 | 24 | 20.99 | | | | | |
| ldpe2 plus 4% cellotape | | 4 | 2.254 | 5.966 | 270 | 36 | 20.08 | | | | | |
| ldpe2 plus 4% cellotape | | 5 | 2.066 | 5.995 | 270 | 28 | 21.80 | | | | | |
| ldpe2 plus 4% cellotape | | 6 | 2.024 | 5.997 | 260 | 28 | 21.42 | | | | | |
| **ldpe2 plus 4% cellotape** | 29/04/2004A | | | | **242** | **28.0** | **19.1** | **0.34** | | | | |
| ldpe2 plus 6% cellotape | | 1 | 2.174 | 5.957 | 190 | 28 | 14.68 | | | | | |
| ldpe2 plus 6% cellotape | | 2 | 2.146 | 5.945 | 240 | 20 | 18.81 | | | | | |
| ldpe2 plus 6% cellotape | | 3 | 2.114 | 5.954 | 180 | 16 | 14.30 | | | | | |
| ldpe2 plus 6% cellotape | | 4 | 2.232 | 5.947 | 150 | 16 | 11.30 | | | | | |
| ldpe2 plus 6% cellotape | | 5 | 2.073 | 5.953 | 130 | 16 | 10.54 | | | | | |
| ldpe2 plus 6% cellotape | | 6 | 2.250 | 5.907 | 140 | 28 | 10.54 | | | | | |
| **ldpe2 plus 6% cellotape** | 29/04/2004B | | | | **172** | **20.7** | **13.4** | **0.32** | | | | |
| ldpe2 plus 2% pvc tape | | 1 | 2.131 | 5.960 | 390 | 60 | 30.70 | | | | | |
| ldpe2 plus 2% pvc tape | | 2 | 2.045 | 5.917 | 370 | 52 | 30.57 | | | | | |
| ldpe2 plus 2% pvc tape | | 3 | 2.086 | 5.956 | 390 | 56 | 31.40 | | | | | |
| ldpe2 plus 2% pvc tape | | 4 | 2.051 | 5.942 | 350 | 48 | 28.72 | | | | | |
| ldpe2 plus 2% pvc tape | | 5 | 2.121 | 5.969 | 360 | 52 | 28.43 | | | | | |
| ldpe2 plus 2% pvc tape | | 6 | 2.142 | 5.969 | 410 | 48 | 32.07 | | | | | |
| **ldpe2 plus 2% pvc tape** | 30/04/2004 | | | | **378** | **52.7** | **30.3** | **0.39** | | | | |
| ldpe2 plus 4% pvc tape | | 1 | 2.232 | 5.957 | 340 | 44 | 25.57 | | | | | |
| ldpe2 plus 4% pvc tape | | 2 | 2.180 | 5.943 | 400 | 56 | 30.87 | | | | | |
| ldpe2 plus 4% pvc tape | | 3 | 2.143 | 5.940 | 390 | 44 | 30.64 | | | | | |
| ldpe2 plus 4% pvc tape | | 4 | 2.180 | 5.939 | 290 | 52 | 22.40 | | | | | |
| ldpe2 plus 4% pvc tape | | 5 | 2.025 | 5.908 | 400 | 52 | 33.43 | | | | | |
| ldpe2 plus 4% pvc tape | | 6 | 2.172 | 5.950 | 350 | 52 | 27.08 | | | | | |
| **ldpe2 plus 4% pvc tape** | 30/04/2004A | | | | **362** | **50.0** | **28.3** | **0.44** | | | | |
| ldpe2 plus 6% pvc tape | | 1 | 2.183 | 5.970 | 300 | 48 | 23.02 | | | | | |
| ldpe2 plus 6% pvc tape | | 2 | 2.188 | 5.974 | 340 | 40 | 26.01 | | | | | |
| ldpe2 plus 6% pvc tape | | 3 | 2.148 | 5.953 | 290 | 40 | 22.68 | | | | | |
| ldpe2 plus 6% pvc tape | | 4 | 2.136 | 5.967 | 320 | 40 | 25.11 | | | | | |
| ldpe2 plus 6% pvc tape | | 5 | 2.105 | 5.971 | 290 | 40 | 23.08 | | | | | |
| ldpe2 plus 6% pvc tape | | 6 | 2.209 | 5.936 | 320 | 44 | 24.41 | | | | | |
| **ldpe2 plus 6% pvc tape** | 30/04/2004B | | | | **310** | **42.0** | **24.1** | **0.46** | | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

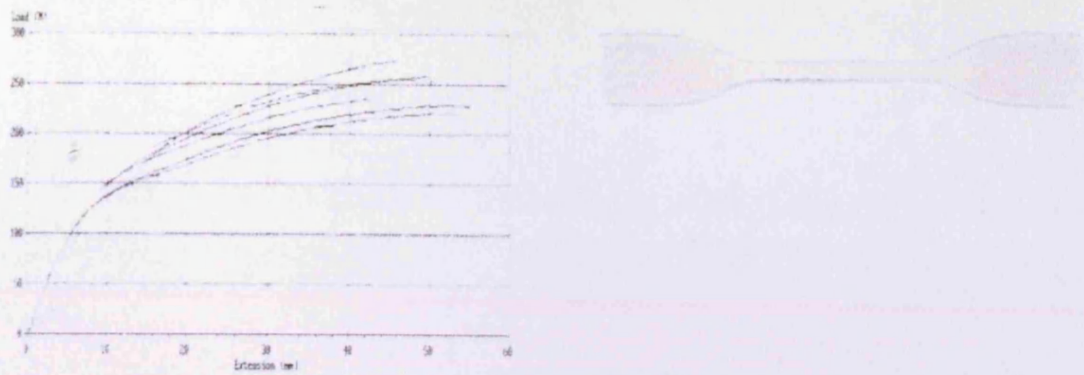
| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| retail film plus 1% PP tape | | 1 | 5.979 | 2.091 | 225 | 80 | 18.00 | | | | | |
| retail film plus 1% PP tape | | 2 | 5.995 | 2.046 | 270 | 68 | 22.01 | | | | | |
| retail film plus 1% PP tape | | 3 | 5.959 | 2.019 | 260 | 48 | 21.62 | | | | | |
| retail film plus 1% PP tape | | 4 | 5.982 | 2.225 | 270 | 56 | 20.29 | | | | | |
| retail film plus 1% PP tape | | 5 | 5.975 | 2.113 | 250 | 56 | 19.80 | | | | | |
| retail film plus 1% PP tape | | 6 | 5.981 | 2.146 | 240 | 72 | 18.70 | | | | | |
| **retail film plus 1% PP tape** | 03/10/2003A | | | | **253** | **63.3** | **20.1** | **2.11** | **35.1** | | | |
| retail film plus 2% PP tape | | 1 | 5.980 | 1.973 | 325 | 36 | 27.55 | | | | | |
| retail film plus 2% PP tape | | 2 | 6.000 | 1.904 | 300 | 40 | 26.27 | | | | | |
| retail film plus 2% PP tape | | 3 | 5.971 | 2.051 | 400 | 40 | 32.66 | | | | | |
| retail film plus 2% PP tape | | 4 | 6.004 | 2.158 | 440 | 40 | 33.97 | | | | | |
| retail film plus 2% PP tape | | 5 | 5.994 | 2.116 | 515 | 28 | 40.61 | | | | | |
| retail film plus 2% PP tape | | 6 | 6.002 | 2.131 | 540 | 36 | 42.22 | | | | | |
| **retail film plus 2% PP tape** | 02/10/2003 | | | | **420** | **36.7** | **33.9** | **0.29** | **48.3** | | | |
| retail film plus 4% PP tape | | 1 | 5.988 | 2.071 | 235 | 56 | 18.95 | | | | | |
| retail film plus 4% PP tape | | 2 | 6.025 | 2.211 | 190 | 100 | 14.27 | | | | | |
| retail film plus 4% PP tape | | 3 | 5.989 | 1.964 | 220 | 48 | 18.71 | | | | | |
| retail film plus 4% PP tape | | 4 | 5.986 | 2.083 | 200 | 96 | 16.04 | | | | | |
| retail film plus 4% PP tape | | 5 | 5.988 | 2.186 | 230 | 36 | 17.57 | | | | | |
| retail film plus 4% PP tape | | 6 | 5.986 | 2.063 | 180 | 56 | 14.57 | | | | | |
| **retail film plus 4% PP tape** | 02/10/2003A | | | | **209** | **65.3** | **16.7** | **0.39** | **39.1** | | | |
| retail film plus 6% PP tape | | 1 | 5.982 | 1.997 | 220 | 28 | 18.42 | | | | | |
| retail film plus 6% PP tape | | 2 | 5.977 | 2.181 | 200 | 80 | 15.34 | | | | | |
| retail film plus 6% PP tape | | 3 | 5.981 | 2.262 | 230 | 80 | 17.01 | | | | | |
| retail film plus 6% PP tape | | 4 | 5.993 | 2.064 | 230 | 48 | 18.60 | | | | | |
| retail film plus 6% PP tape | | 5 | 5.986 | 2.074 | 215 | 72 | 17.32 | | | | | |
| retail film plus 6% PP tape | | 6 | 5.981 | 2.130 | 235 | 40 | 18.45 | | | | | |
| **retail film plus 6% PP tape** | 03/10/2003 | | | | **222** | **58.0** | **17.5** | **2.08** | **34.9** | | | |
| 100% masterbatch | | 1 | 5.980 | 2.171 | 250 | 12 | 19.26 | | | | | |
| 100% masterbatch | | 2 | 5.993 | 1.794 | 225 | 8 | 20.93 | | | | | |
| 100% masterbatch | | 3 | 6.008 | 2.289 | 270 | 12 | 19.63 | | | | | |
| 100% masterbatch | | 4 | 6.011 | 2.232 | 260 | 12 | 19.38 | | | | | |
| 100% masterbatch | | 5 | 6.014 | 2.195 | 255 | 12 | 19.32 | | | | | |
| 100% masterbatch | | 6 | 5.987 | 2.225 | 255 | 12 | 19.14 | | | | | |
| **100% masterbatch** | 07/11/2003 | | | | **253** | **11.3** | **19.6** | **0.14** | **59.8** | | | |
| 90% masterbatch | | 1 | 6.015 | 2.270 | 290 | 16 | 21.24 | | | | | |
| 90% masterbatch | | 2 | 5.994 | 2.229 | 265 | 12 | 19.84 | | | | | |
| 90% masterbatch | | 3 | 6.005 | 2.088 | 230 | 12 | 18.35 | | | | | |
| 90% masterbatch | | 4 | 6.017 | 2.173 | 275 | 12 | 21.03 | | | | | |
| 90% masterbatch | | 5 | 6.006 | 2.170 | 260 | 12 | 19.95 | | | | | |
| 90% masterbatch | | 6 | 5.994 | 2.173 | 270 | 12 | 20.73 | | | | | |
| **90% masterbatch** | 11/11/2003 | | | | **265** | **12.7** | **20.2** | **0.14** | **49.6** | | | |
| 80% masterbatch | | 1 | 5.964 | 2.211 | 310 | 24 | 23.51 | | | | | |
| 80% masterbatch | | 2 | 6.001 | 2.122 | 280 | 16 | 21.99 | | | | | |
| 80% masterbatch | | 3 | 5.986 | 2.179 | 290 | 20 | 22.23 | | | | | |
| 80% masterbatch | | 4 | 5.998 | 2.164 | 300 | 24 | 23.11 | | | | | |
| 80% masterbatch | | 5 | 5.997 | 2.031 | 270 | 16 | 22.17 | | | | | |
| 80% masterbatch | | 6 | 6.004 | 2.174 | 280 | 24 | 21.45 | | | | | |
| **80% masterbatch** | 12/11/2003 | | | | **288** | **20.7** | **22.4** | **0.25** | **49.8** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| 70% masterbatch | | | | | | | | | | | | |
| 70% masterbatch | | 2 | 5.999 | 2.066 | 235 | 16 | 18.96 | | | | | |
| 70% masterbatch | | 3 | 5.976 | 1.939 | 230 | 16 | 19.85 | | | | | |
| 70% masterbatch | | 4 | 5.994 | 2.082 | 265 | 24 | 21.24 | | | | | |
| 70% masterbatch | | 5 | 5.998 | 2.157 | 300 | 24 | 23.19 | | | | | |
| 70% masterbatch | | 6 | 6.010 | 2.182 | 300 | 28 | 22.88 | | | | | |
| **70% masterbatch** | 12/11/2003A | | | | **266** | **21.6** | **21.2** | **0.26** | **47.7** | | | |
| 50% masterbatch | | 1 | 5.991 | 1.996 | 255 | 40 | 21.33 | | | | | |
| 50% masterbatch | | 2 | 5.998 | 2.035 | 260 | 36 | 21.30 | | | | | |
| 50% masterbatch | | 3 | 6.011 | 2.151 | 300 | 40 | 23.20 | | | | | |
| 50% masterbatch | | 4 | 6.018 | 2.262 | 370 | 40 | 27.18 | | | | | |
| 50% masterbatch | | 5 | 5.974 | 2.127 | 300 | 44 | 23.61 | | | | | |
| 50% masterbatch | | 6 | 5.951 | 1.978 | 260 | 36 | 22.09 | | | | | |
| **50% masterbatch** | 13/11/2003 | | | | **291** | **39.3** | **23.1** | **0.33** | **45.6** | | | |
| 30% masterbatch | | 1 | 5.992 | 2.066 | 345 | 48 | 27.87 | | | | | |
| 30% masterbatch | | | | | | | | | | | | |
| 30% masterbatch | | 3 | 5.987 | 2.032 | 350 | 52 | 28.78 | | | | | |
| 30% masterbatch | | 4 | 6.002 | 2.283 | 370 | 48 | 27.01 | | | | | |
| 30% masterbatch | | 5 | 5.986 | 2.096 | 350 | 40 | 27.89 | | | | | |
| 30% masterbatch | | 6 | 5.992 | 2.002 | 310 | 40 | 25.85 | | | | | |
| **30% masterbatch** | 13/11/2003A | | | | **345** | **45.6** | **27.5** | **0.40** | **41.7** | | | |
| 20% masterbatch | | 1 | 6.006 | 2.178 | 320 | 44 | 24.47 | | | | | |
| 20% masterbatch | | 2 | 5.747 | 2.157 | 330 | 44 | 26.62 | | | | | |
| 20% masterbatch | | 3 | 5.999 | 2.030 | 350 | 39 | 28.75 | | | | | |
| 20% masterbatch | | 4 | 5.989 | 2.206 | 315 | 39 | 23.84 | | | | | |
| 20% masterbatch | | 5 | 5.998 | 2.198 | 395 | 40 | 29.96 | | | | | |
| 20% masterbatch | | 6 | 5.986 | 2.090 | 320 | 40 | 25.58 | | | | | |
| **20% masterbatch** | 17/11/2003 | | | | **338** | **41.0** | **26.5** | **0.43** | **35.5** | | | |
| 10% masterbatch | | 1 | 5.963 | 1.975 | 325 | 48 | 27.60 | | | | | |
| 10% masterbatch | | 2 | 5.995 | 2.057 | 380 | 52 | 30.82 | | | | | |
| 10% masterbatch | | 3 | 5.983 | 1.979 | 375 | 48 | 31.68 | | | | | |
| 10% masterbatch | | 4 | 5.994 | 1.969 | 375 | 44 | 31.78 | | | | | |
| 10% masterbatch | | 5 | 5.996 | 2.194 | 420 | 44 | 31.93 | | | | | |
| 10% masterbatch | | 6 | 5.997 | 2.046 | 380 | 40 | 30.97 | | | | | |
| **10% masterbatch** | 17/11/2003A | | | | **376** | **46.0** | **30.8** | **0.43** | **38.2** | | | |
| 100% ldpe | | 1 | 5.947 | 1.977 | 355 | 48 | 30.20 | | | | | |
| 100% ldpe | | 2 | 5.997 | 2.196 | 450 | 44 | 34.17 | | | | | |
| 100% ldpe | | 3 | 5.965 | 1.981 | 340 | 39 | 28.78 | | | | | |
| 100% ldpe | | 4 | 6.003 | 1.922 | 340 | 39 | 29.47 | | | | | |
| 100% ldpe | | 5 | 5.985 | 2.120 | 320 | 40 | 25.22 | | | | | |
| 100% ldpe | | 6 | 5.980 | 2.083 | 365 | 56 | 29.30 | | | | | |
| **100% ldpe** | 17/11/2003B | | | | **362** | **44.3** | **29.5** | **0.45** | **32.2** | | | |
| c/bags plus 20% Erema | | 1 | 6.008 | 2.092 | 520 | 12 | 41.37 | | | | | |
| c/bags plus 20% Erema | | 2 | 6.005 | 2.050 | 460 | 8 | 37.37 | | | | | |
| c/bags plus 20% Erema | | 3 | 6.010 | 2.027 | 500 | 16 | 41.04 | | | | | |
| c/bags plus 20% Erema | | 4 | 6.007 | 2.056 | 540 | 12 | 43.74 | | | | | |
| c/bags plus 20% Erema | | 5 | 6.006 | 2.116 | 505 | 16 | 39.73 | | | | | |
| c/bags plus 20% Erema | | 6 | 6.000 | 2.044 | 480 | 16 | 39.14 | | | | | |
| **c/bags plus 20% Erema** | 20/11/2003 | | | | **501** | **13.3** | **40.4** | **0.20** | **64.8** | | | |

Table H1: Tensile, MFI, XRD and GRPC test results from all tested specimens (continued)

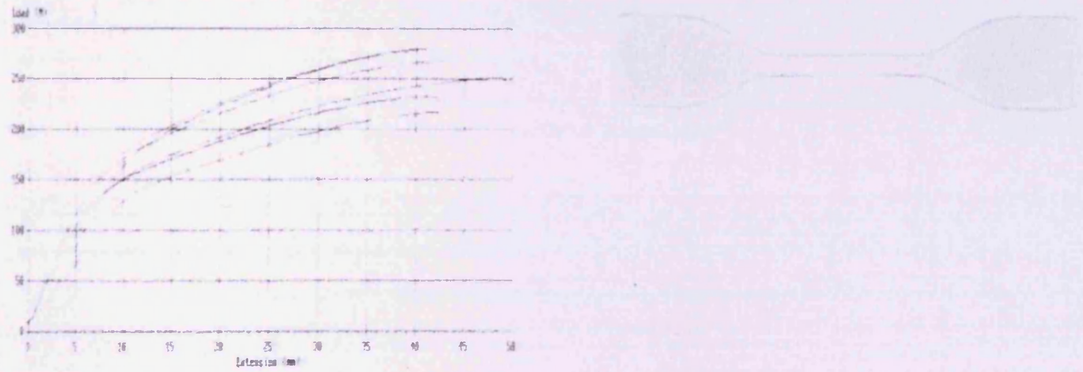
| Test | | P/N | Width | Thickn | Max load | Max. El | UTS | MFI | XTAL | PI | Mn | Mw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm) | (mm) | (N) | (%) | (N/mm2) | (g/10min) | (%) | | | |
| c/bags plus 40% Erema | | 1 | 6.006 | 2.181 | 540 | 12 | 41.22 | | | | | |
| c/bags plus 40% Erema | | 2 | 5.987 | 2.006 | 400 | 12 | 33.31 | | | | | |
| c/bags plus 40% Erema | | 3 | 5.998 | 2.066 | 440 | 12 | 35.52 | | | | | |
| c/bags plus 40% Erema | | 4 | 5.993 | 2.037 | 440 | 16 | 36.05 | | | | | |
| c/bags plus 40% Erema | | 5 | 5.983 | 2.096 | 400 | 12 | 31.90 | | | | | |
| c/bags plus 40% Erema | | 6 | 6.009 | 2.041 | 440 | 16 | 35.88 | | | | | |
| **c/bags plus 40% Erema** | 20/11/2003A | | | | **443** | **13.3** | **35.6** | **0.34** | **49.8** | **8.95** | **15050** | **135000** |
| c/bags plus 60% Erema | | 1 | 5.968 | 1.974 | 370 | 20 | 31.41 | | | | | |
| c/bags plus 60% Erema | | 2 | 5.984 | 2.011 | 380 | 16 | 31.58 | | | | | |
| c/bags plus 60% Erema | | 3 | 6.009 | 2.168 | 530 | 16 | 40.68 | | | | | |
| c/bags plus 60% Erema | | 4 | 6.006 | 2.234 | 470 | 20 | 35.03 | | | | | |
| c/bags plus 60% Erema | | 5 | 5.996 | 2.147 | 400 | 16 | 31.08 | | | | | |
| c/bags plus 60% Erema | | 6 | 6.002 | 2.149 | 470 | 20 | 36.45 | | | | | |
| **c/bags plus 60% Erema** | 21/11/2003 | | | | **437** | **18.0** | **34.4** | **0.52** | **38.6** | **6.6** | **18350** | **121000** |
| c/bags plus 80% Erema | | 1 | 5.971 | 1.975 | 250 | 28 | 21.20 | | | | | |
| c/bags plus 80% Erema | | 2 | 6.003 | 2.106 | 290 | 20 | 22.94 | | | | | |
| c/bags plus 80% Erema | | 3 | 5.974 | 2.103 | 290 | 20 | 23.08 | | | | | |
| c/bags plus 80% Erema | | 4 | 6.004 | 2.219 | 320 | 20 | 24.02 | | | | | |
| c/bags plus 80% Erema | | 5 | 5.984 | 1.956 | 240 | 60 | 20.50 | | | | | |
| c/bags plus 80% Erema | | 6 | 6.003 | 2.068 | 350 | 20 | 28.19 | | | | | |
| **c/bags plus 80% Erema** | 21/11/2003A | | | | **290** | **28.0** | **23.3** | **0.71** | **37.5** | | | |
| c/bags plus 90% Erema | | 1 | 5.982 | 1.967 | 190 | 92 | 16.15 | | | | | |
| c/bags plus 90% Erema | | 2 | 5.995 | 2.106 | 305 | 52 | 24.16 | | | | | |
| c/bags plus 90% Erema | | 3 | | | | | | | | | | |
| c/bags plus 90% Erema | | 4 | 6.007 | 2.020 | 250 | 44 | 20.60 | | | | | |
| c/bags plus 90% Erema | | 5 | 5.979 | 2.040 | 200 | 68 | 16.40 | | | | | |
| c/bags plus 90% Erema | | 6 | 5.998 | 2.079 | 250 | 76 | 20.05 | | | | | |
| **c/bags plus 90% Erema** | 21/11/2003B | | | | **239** | **66.4** | **19.5** | **0.86** | **28.6** | | | |



(a) tensile test results

(b) specimen image

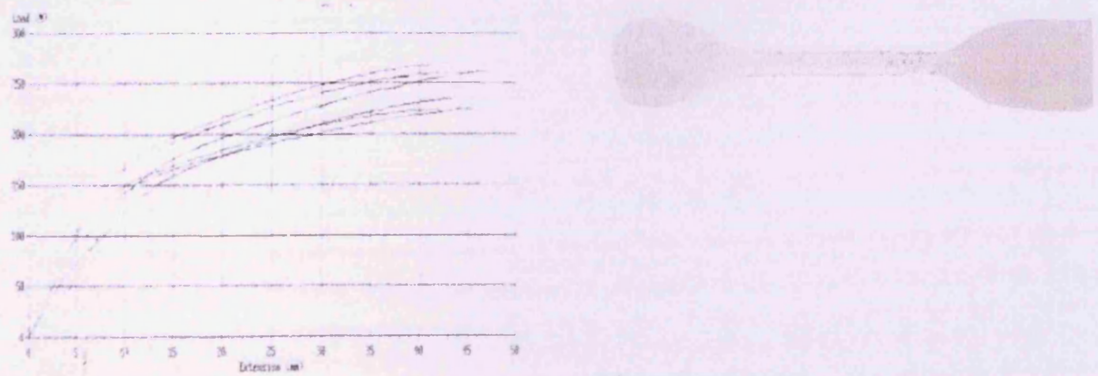
FIGURE H1 : 21/03/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 0 CYCLES



(a) tensile test results

(b) specimen image

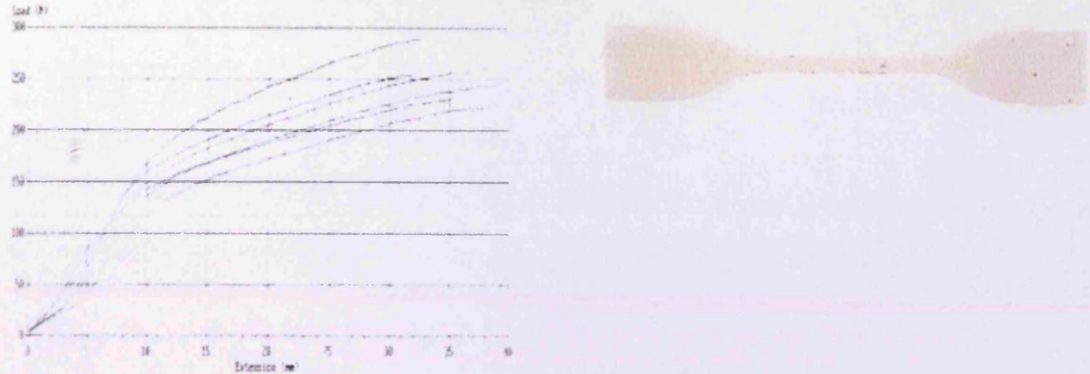
FIGURE H2 : 25/03/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 1 CYCLE



(a) tensile test results

(b) specimen image

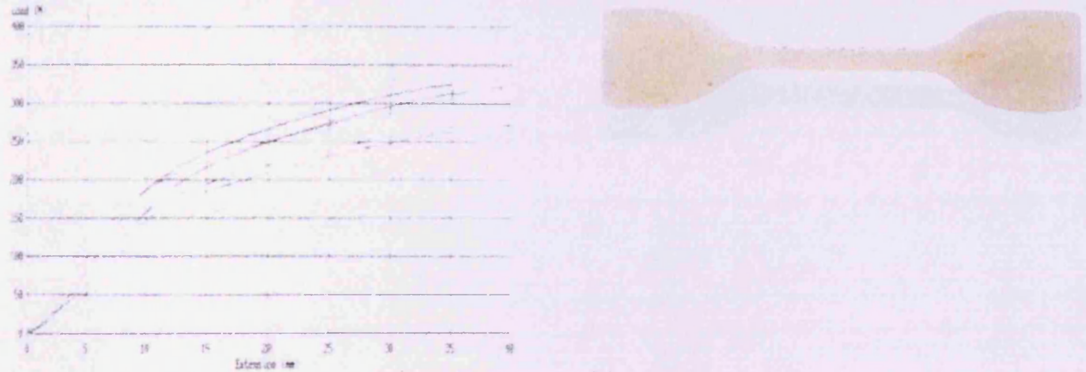
FIGURE H3 : 01/04/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 2 CYCLES



(a) tensile test results

(b) specimen image

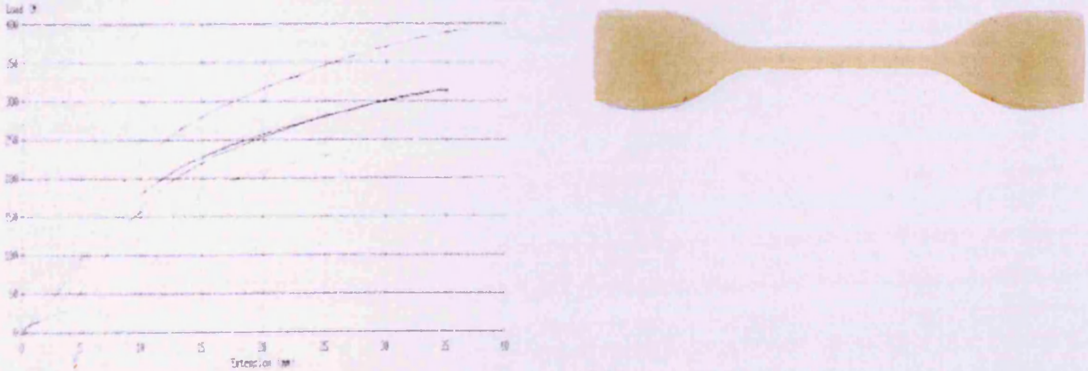
FIGURE H4 : 03/04/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 3 CYCLES



(a) tensile test results

(b) specimen image

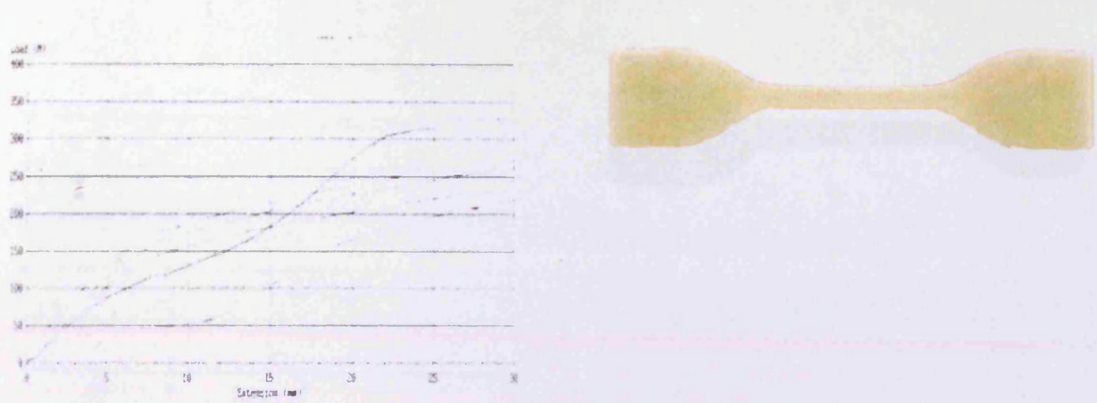
FIGURE H5 : 07/04/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 4 CYCLES



(a) tensile test results

(b) specimen image

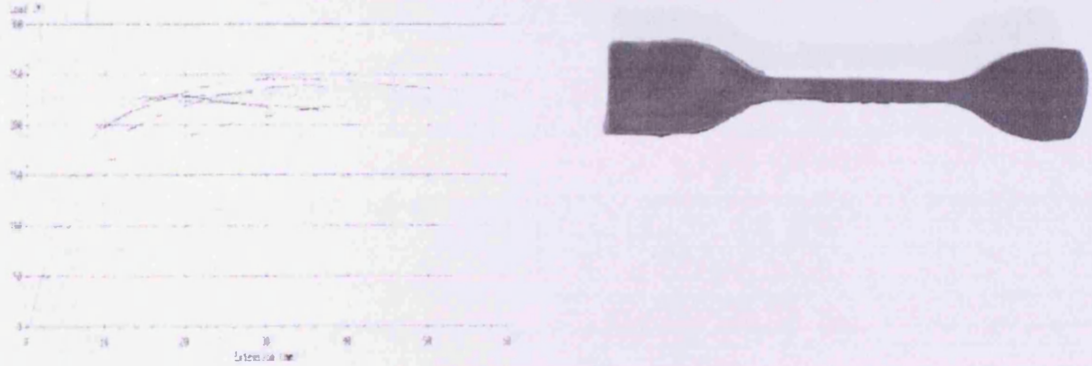
FIGURE H6 : 08/04/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 5 CYCLES



(a) tensile test results

(b) specimen image

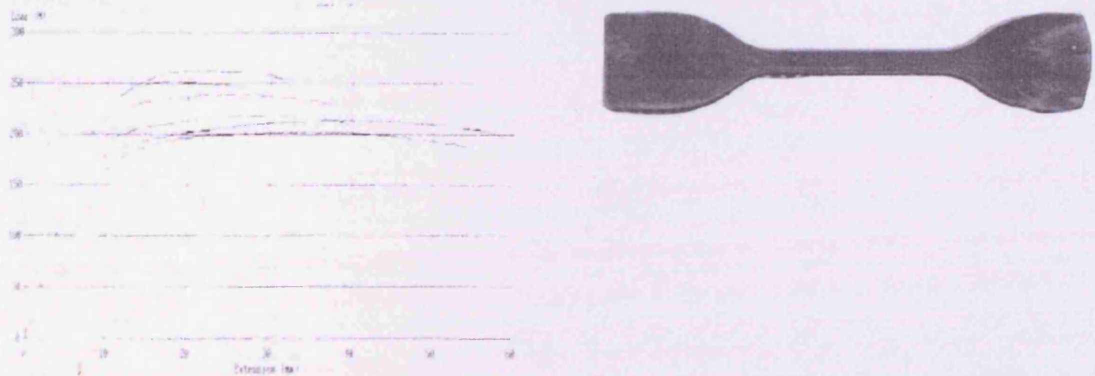
FIGURE H7 : 11/04/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 6 CYCLES



(a) tensile test results

(b) specimen image

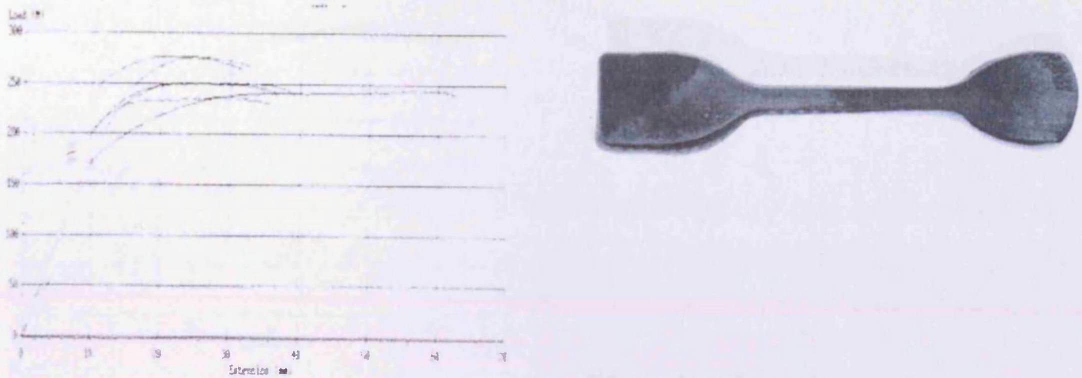
FIGURE H8 : 14/04/03 MATERIAL: EREMA PE MIX CLASS: PLUS 0 CYCLES



(a) tensile test results

(b) specimen image

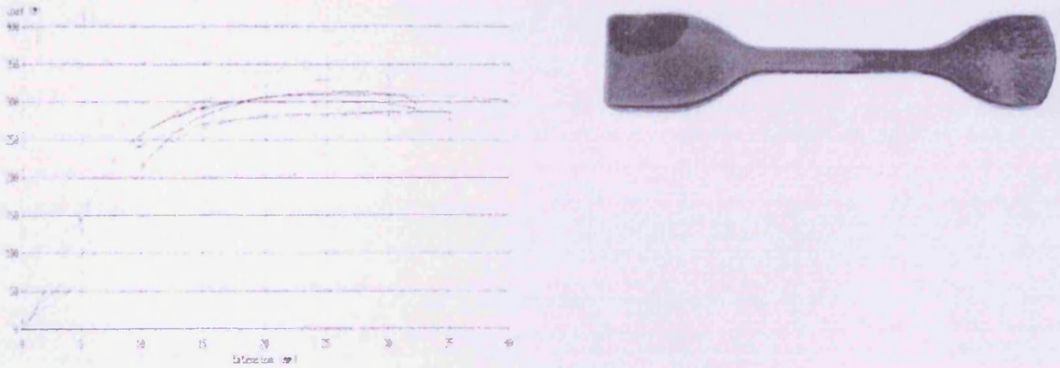
FIGURE H9 : 17/04/03 MATERIAL: EREMA PE MIX CLASS: PLUS 1 CYCLE



(a) tensile test results

(b) specimen image

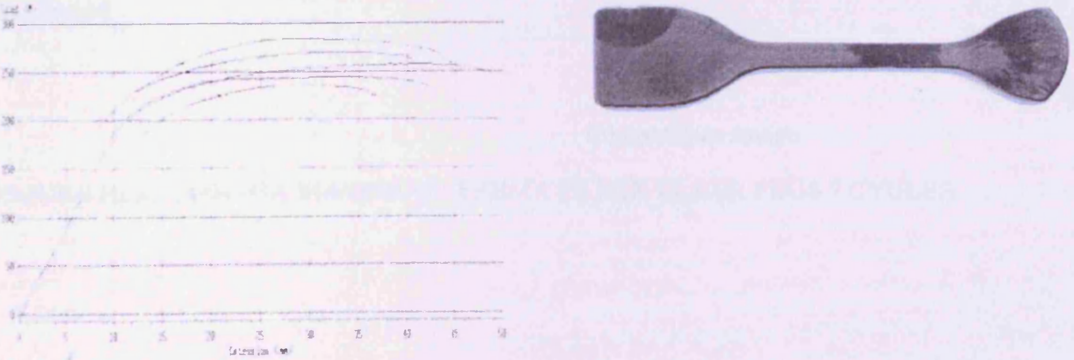
FIGURE H10 : 23/04/03 MATERIAL: EREMA PE MIX CLASS: PLUS 2 CYCLES



(a) tensile test results

(b) specimen image

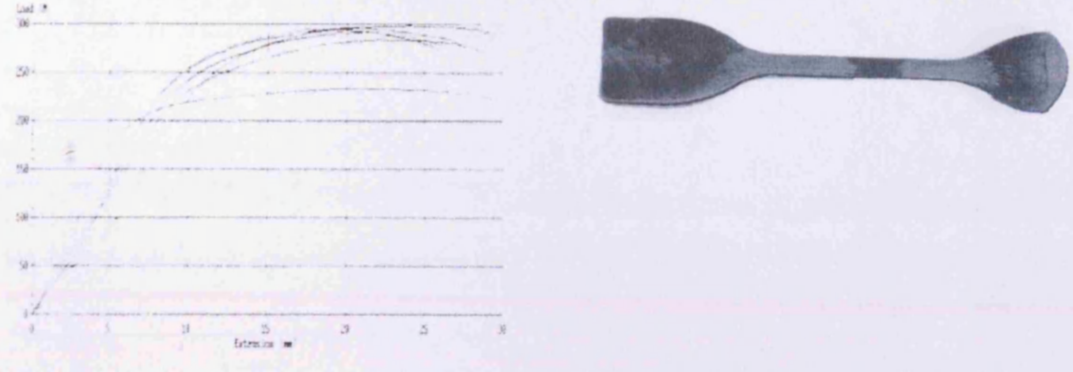
FIGURE H11 : 23/04/03A MATERIAL: EREMA PE MIX CLASS: PLUS 3 CYCLES



(a) tensile test results

(b) specimen image

FIGURE H12 : 24/04/03 MATERIAL: EREMA PE MIX CLASS: PLUS 4 CYCLES



(a) tensile test results

(b) specimen image

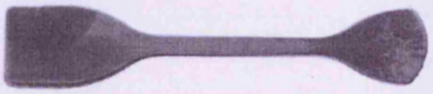
FIGURE H13 : 24/04/03A MATERIAL: EREMA PE MIX CLASS: PLUS 5 CYCLES

(a) tensile test results

(b) specimen image

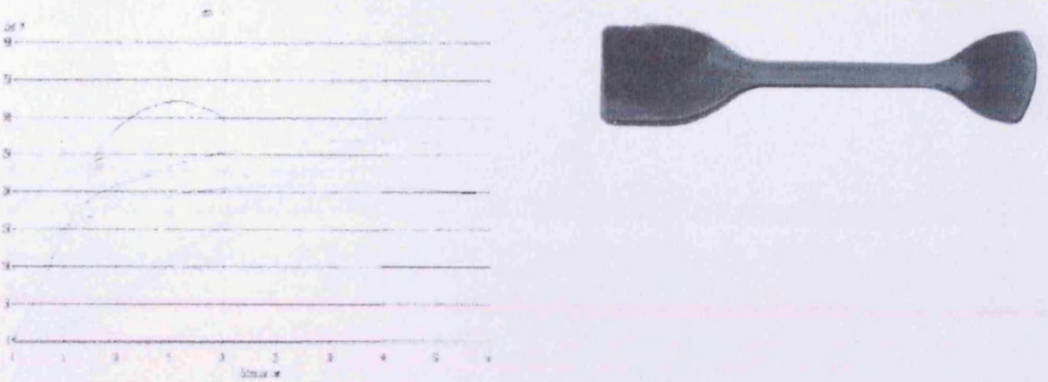
FIGURE H14 : 28/04/03 MATERIAL: EREMA PE MIX CLASS: PLUS 6 CYCLES

(no image)



(b) specimen image

FIGURE H15 : 28/04/03A MATERIAL: EREMA PE MIX CLASS: PLUS 7 CYCLES

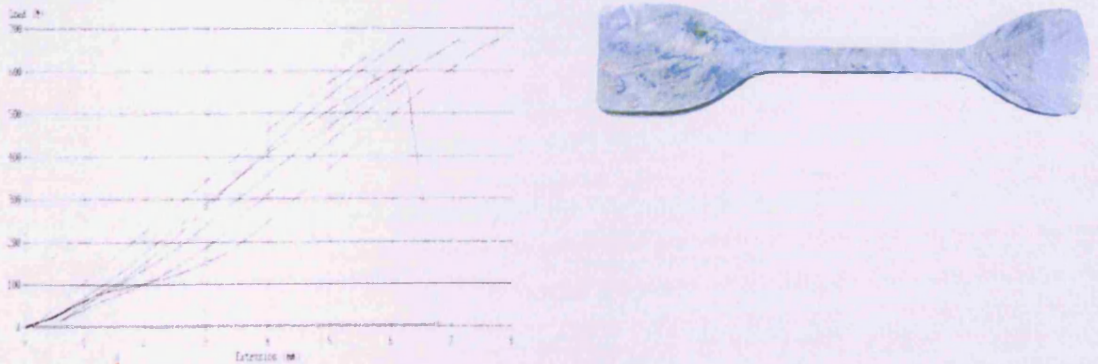


(a) tensile test results (b) specimen image

FIGURE H16 : 28/04/03B MATERIAL: EREMA PE MIX CLASS: PLUS 8 CYCLES

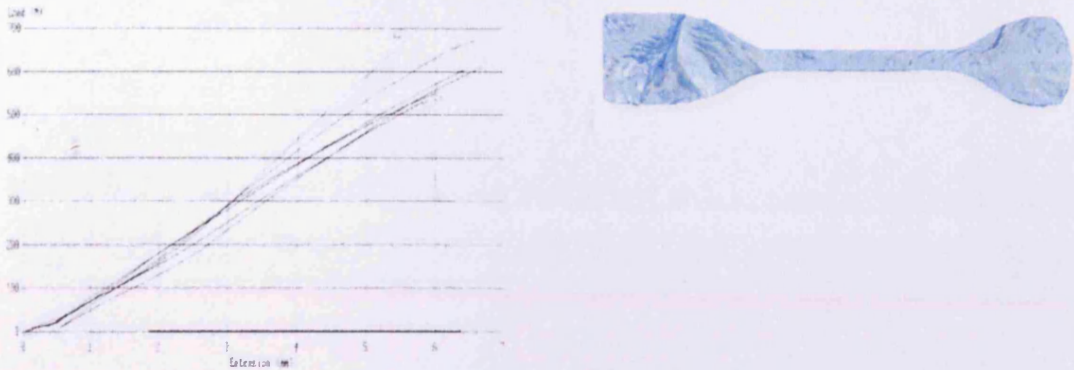
(a) tensile test results (b) specimen image

FIGURE H17 : 02/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 0 CYCLES



(a) tensile test results (b) specimen image

FIGURE H18 : 06/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 1 CYCLE

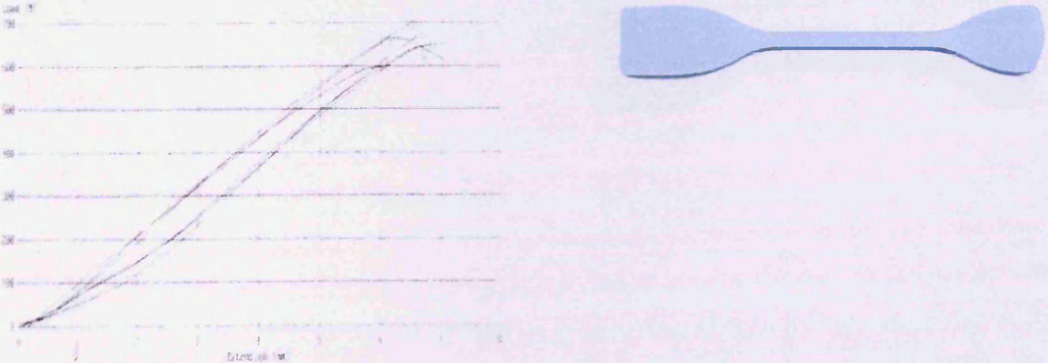


(a) tensile test results (b) specimen image

FIGURE H19 : 08/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 2 CYCLES

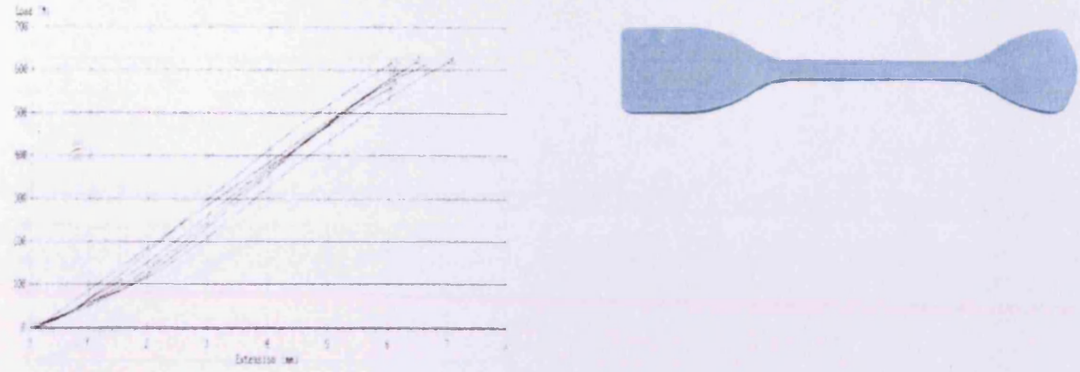
(a) tensile test results (b) specimen image

FIGURE H20 : 16/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 3 CYCLES



(a) tensile test results (b) specimen image

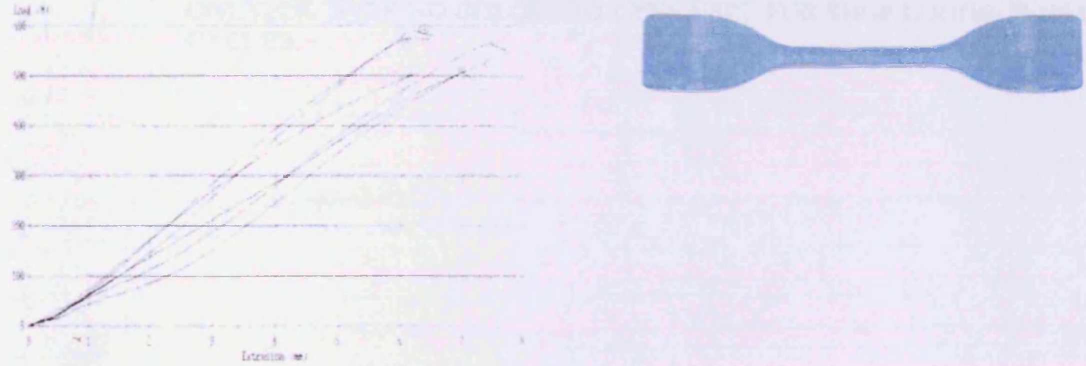
FIGURE H21 : 19/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 4 CYCLES



(a) tensile test results

(b) specimen image

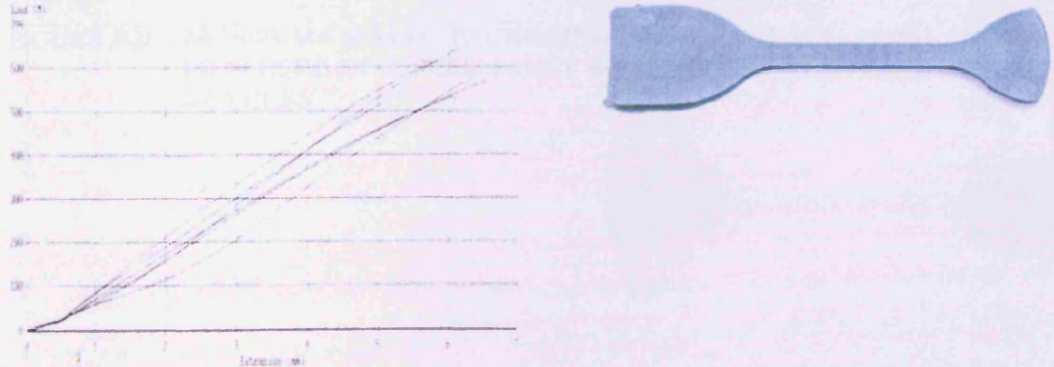
FIGURE H22 : 19/05/03A MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 5 CYCLES



(a) tensile test results

(b) specimen image

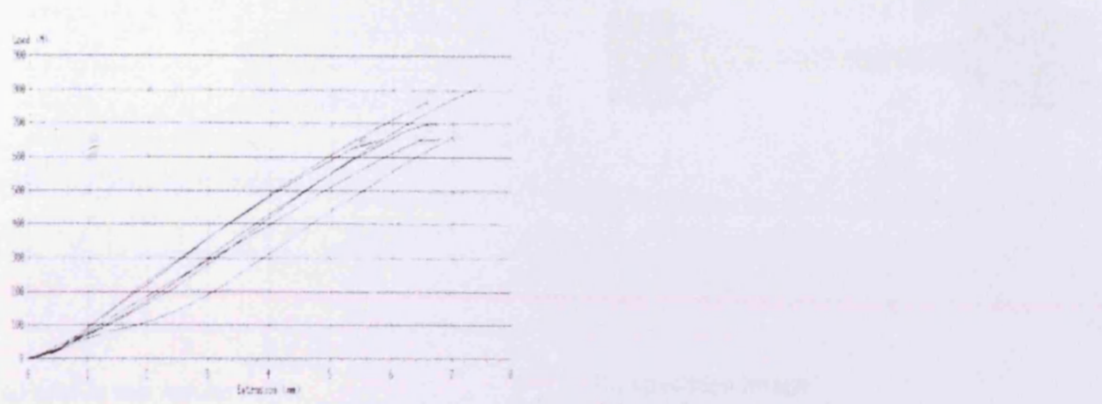
FIGURE H23 : 20/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 6 CYCLES



(a) tensile test results

(b) specimen image

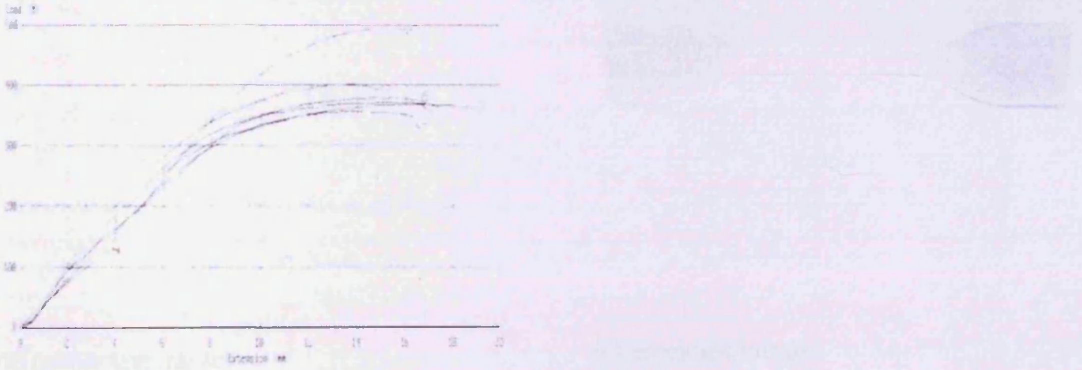
FIGURE H24 : 20/05/03A MATERIAL: SUPERMARKET BAGS PE CLASS: PLUS 7 CYCLES



(a) tensile test results

(b) specimen image

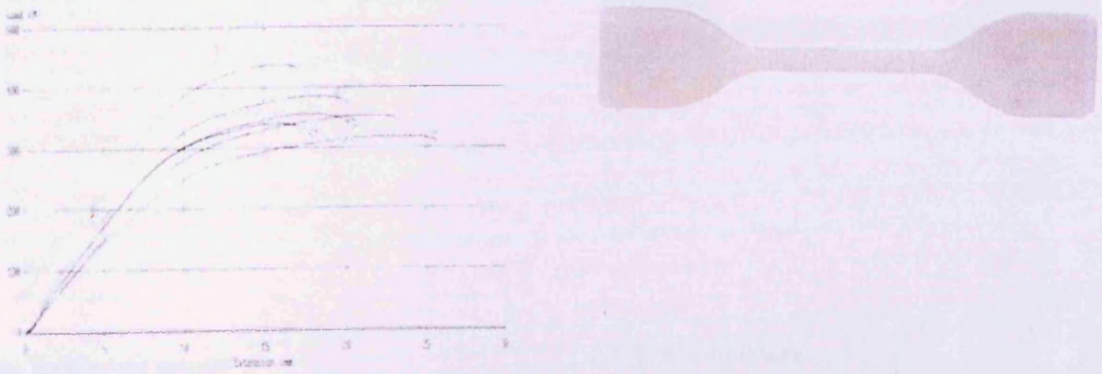
FIGURE H25 : 27/05/03 MATERIAL: SUPERMARKET BAGS PE CLASS: WHITE PORTION ONLY, I.E. WITH NO COLOURED DYES USED FOR SHOP LOGOS. PLUS 0 CYCLES.



(a) tensile test results

(b) specimen image

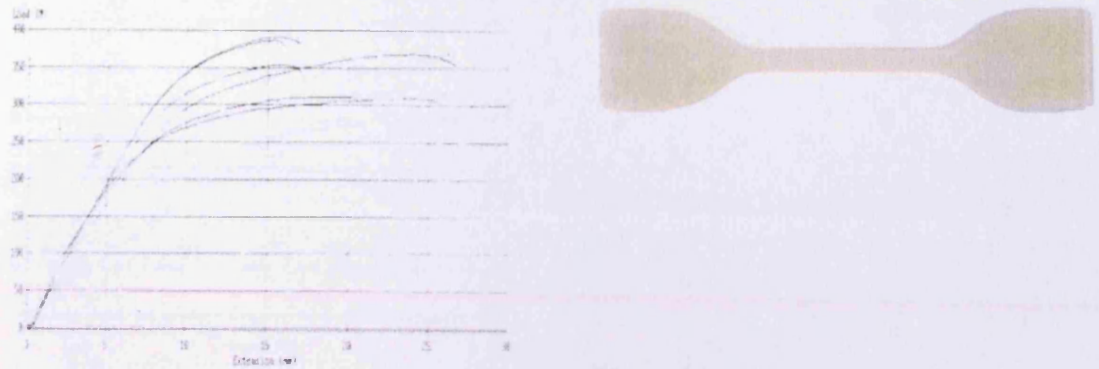
FIGURE H26 : 28/05/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 0 CYCLES



(a) tensile test results

(b) specimen image

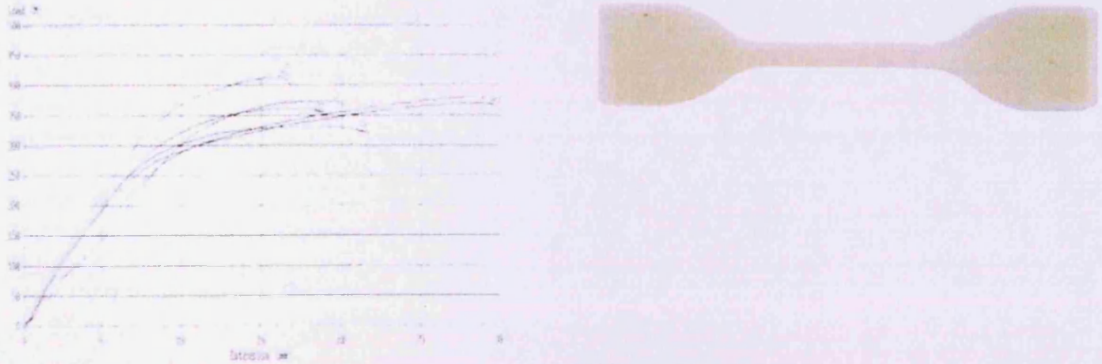
FIGURE H27 : 02/06/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 1 CYCLE



(a) tensile test results

(b) specimen image

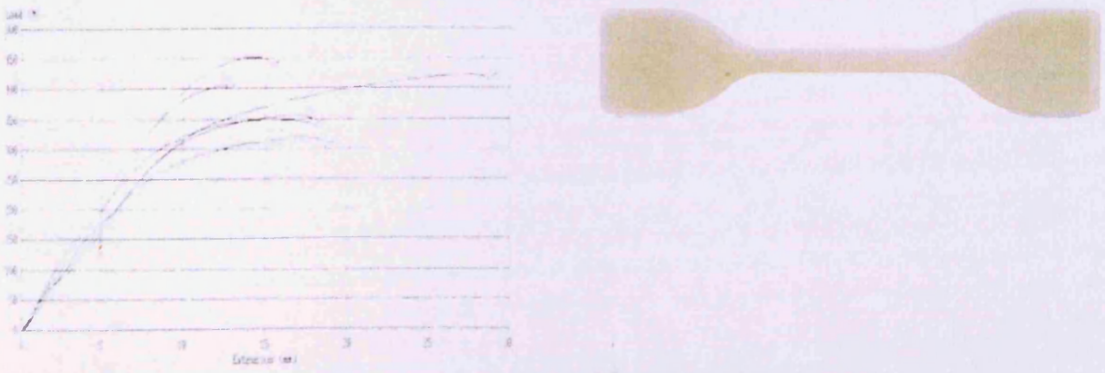
FIGURE H28 : 03/06/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 2 CYCLES



(a) tensile test results

(b) specimen image

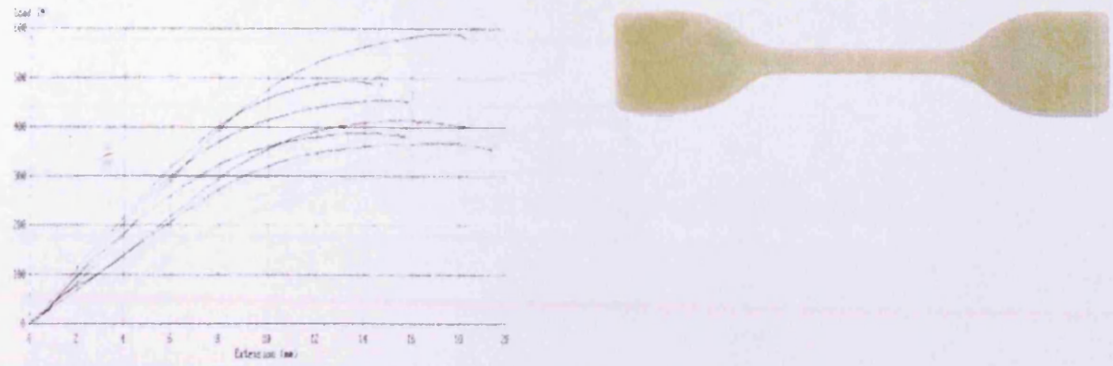
FIGURE H29 : 04/06/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 3 CYCLES.



(a) tensile test results

(b) specimen image

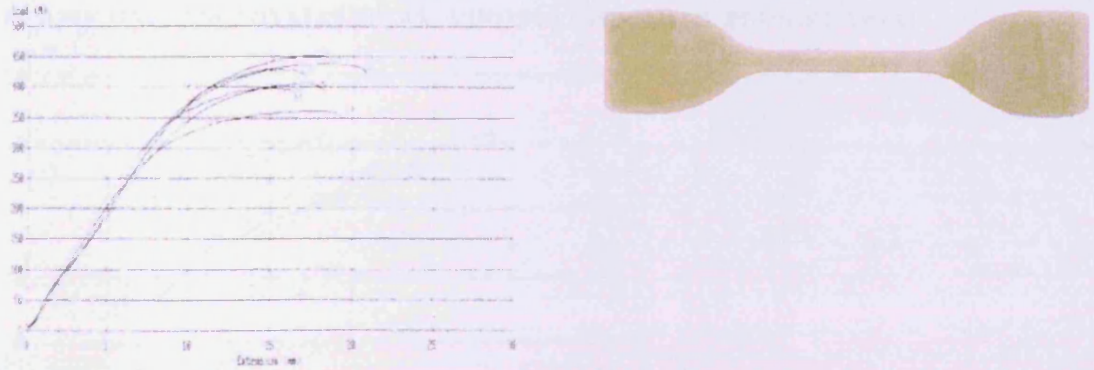
FIGURE H30 : 04/06/03A MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 4 CYCLES



(a) tensile test results

(b) specimen image

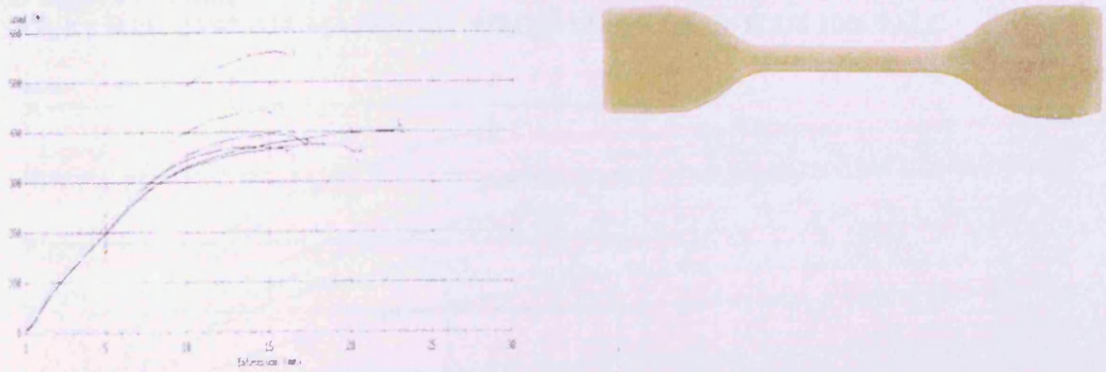
FIGURE H31 : 05/06/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 5 CYCLES



(a) tensile test results

(b) specimen image

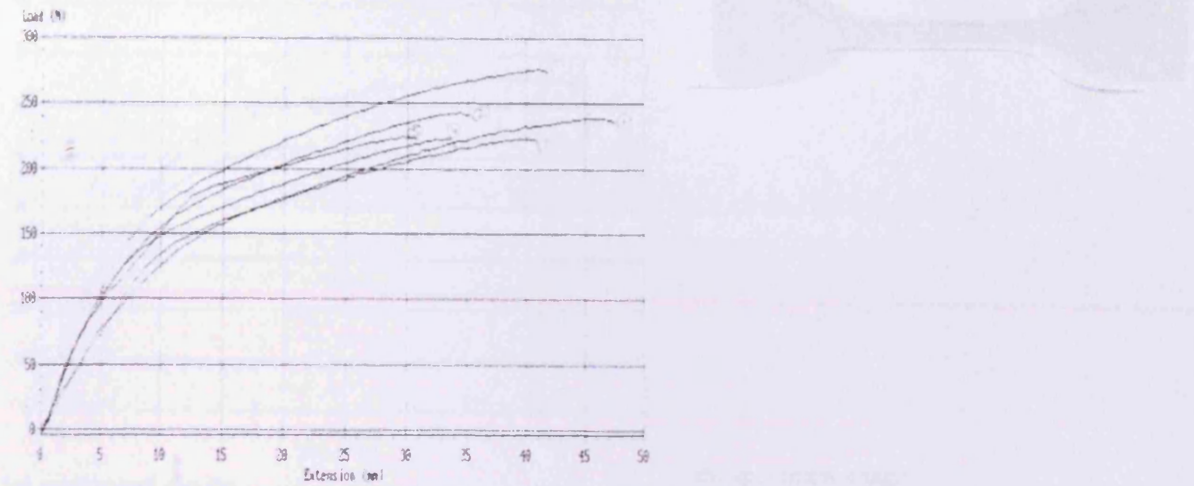
FIGURE H32 : 05/06/03A MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 6 CYCLES



(a) tensile test results

(b) specimen image

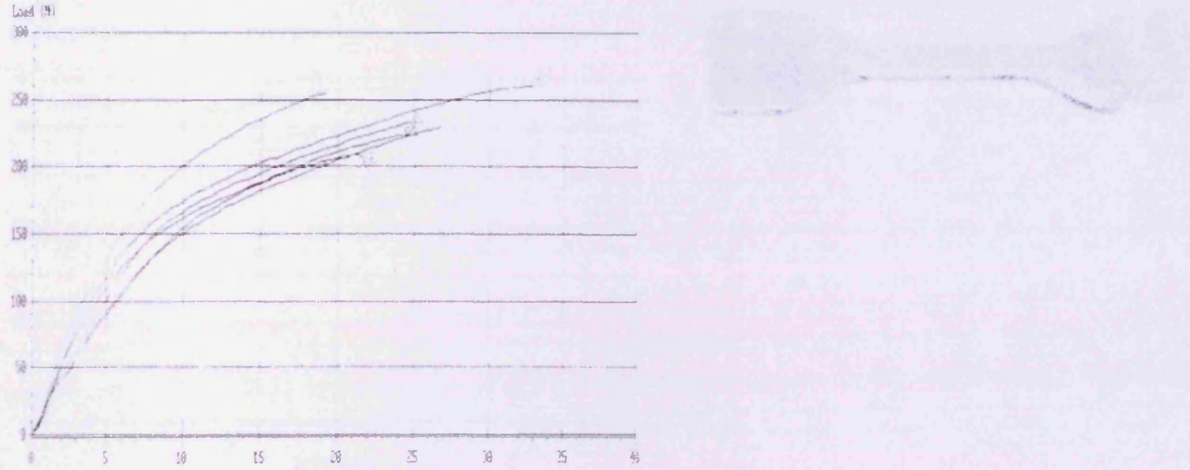
FIGURE H33 : 05/06/03B MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 7 CYCLES



(a) tensile test results

(b) specimen image

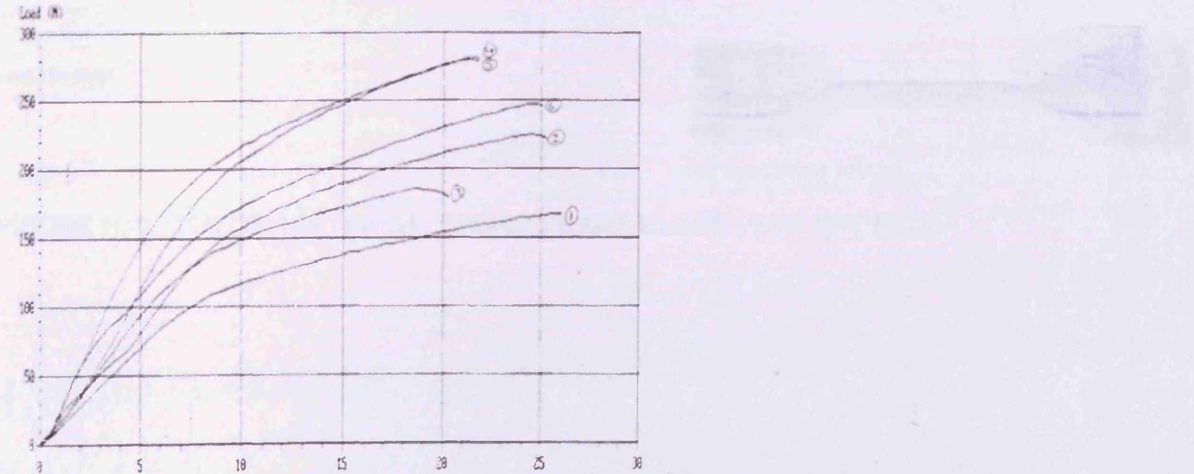
FIGURE H34 : 23/07/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 5% TALC



(b) specimen image

(a) tensile test results

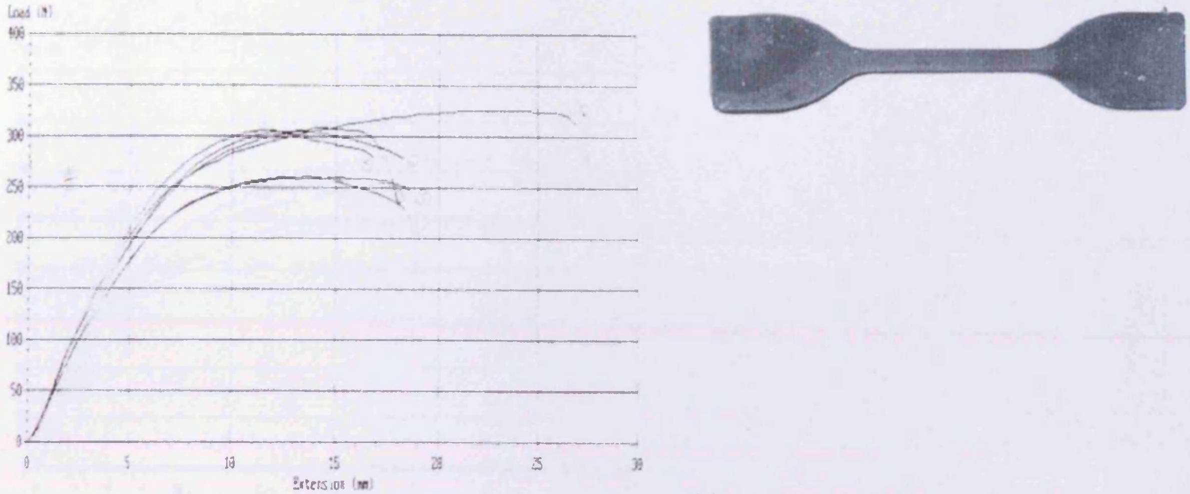
FIGURE H35 : 23/07/03A MATERIAL: VIRGIN LDPE CLASS: PLUS 10% TALC



(b) specimen image

(a) tensile test results

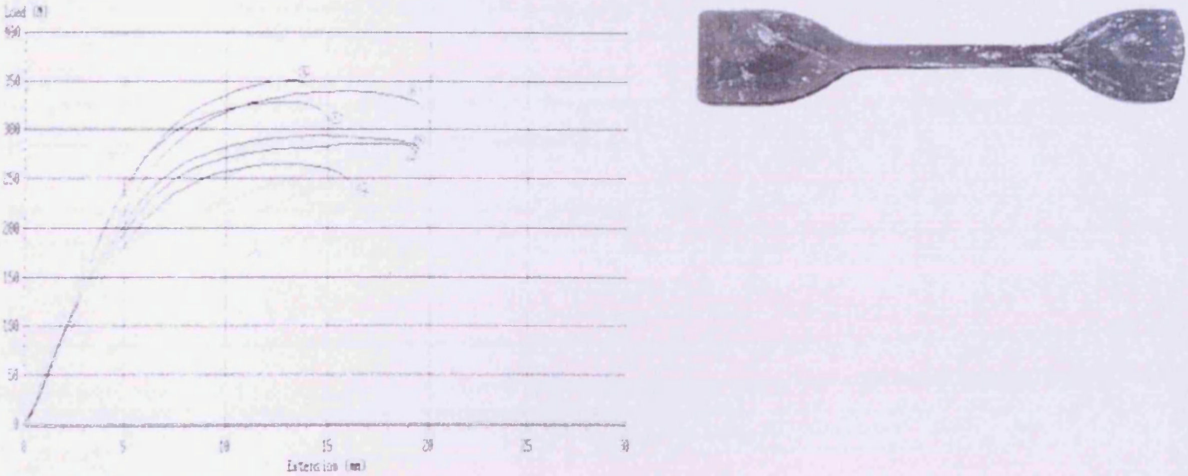
FIGURE H36 : 24/07/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 15% TALC



(a) tensile test results

(b) specimen image

FIGURE H37 : 24/07/03A MATERIAL: EREMA PE MIX CLASS: PLUS 5% TALC

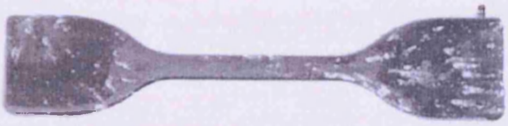


(a) tensile test results

(b) specimen image

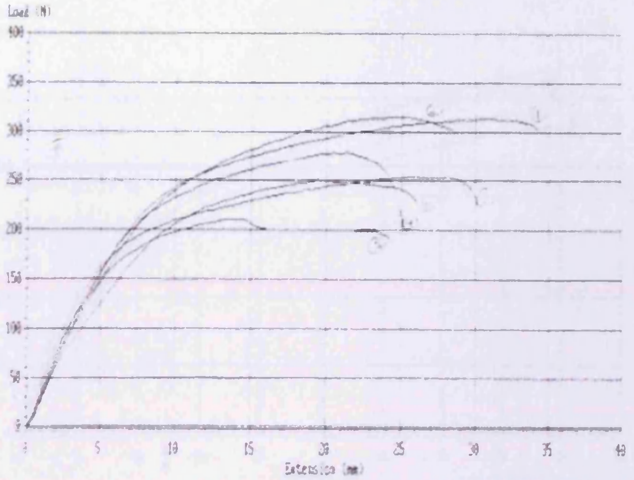
FIGURE H38 : 24/07/03B MATERIAL: EREMA PE MIX CLASS: PLUS 10% TALC

(no image)



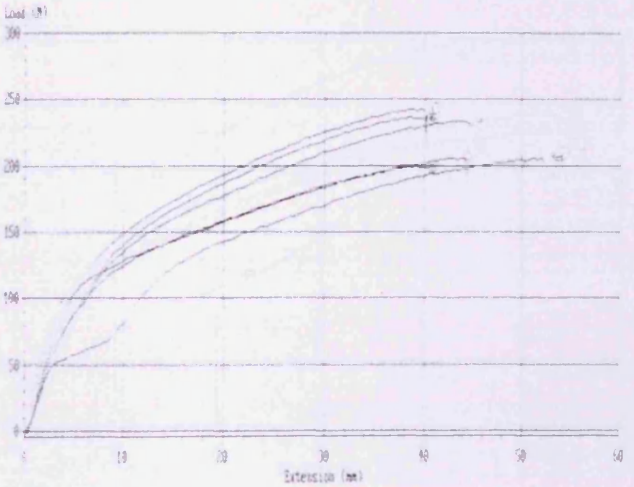
(b) specimen image

FIGURE H39 : 25/07/03 MATERIAL: EREMA PE MIX CLASS: PLUS 15% TALC



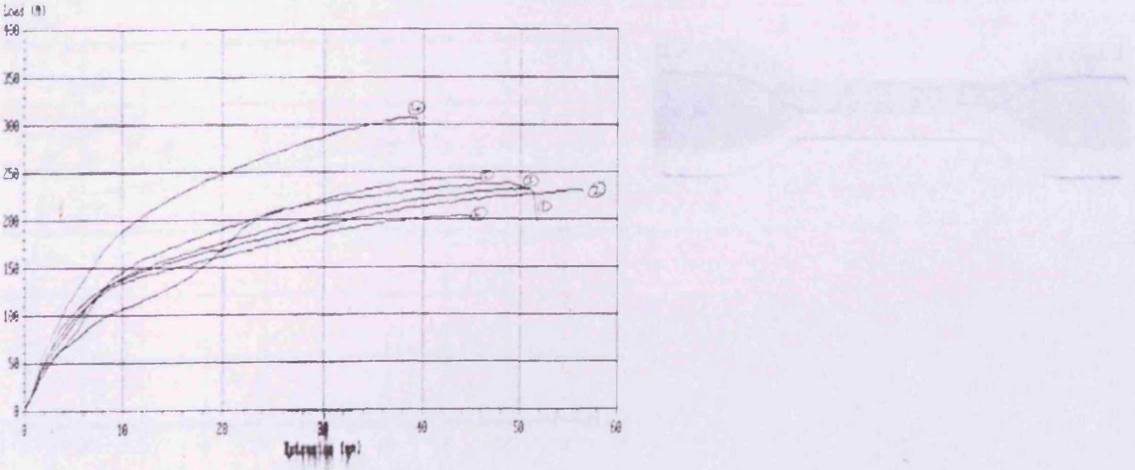
(a) tensile test results (b) specimen image

FIGURE H40 : 12/08/03 MATERIAL: LLDPE CLING FILM CLASS: DOMESTIC FILM



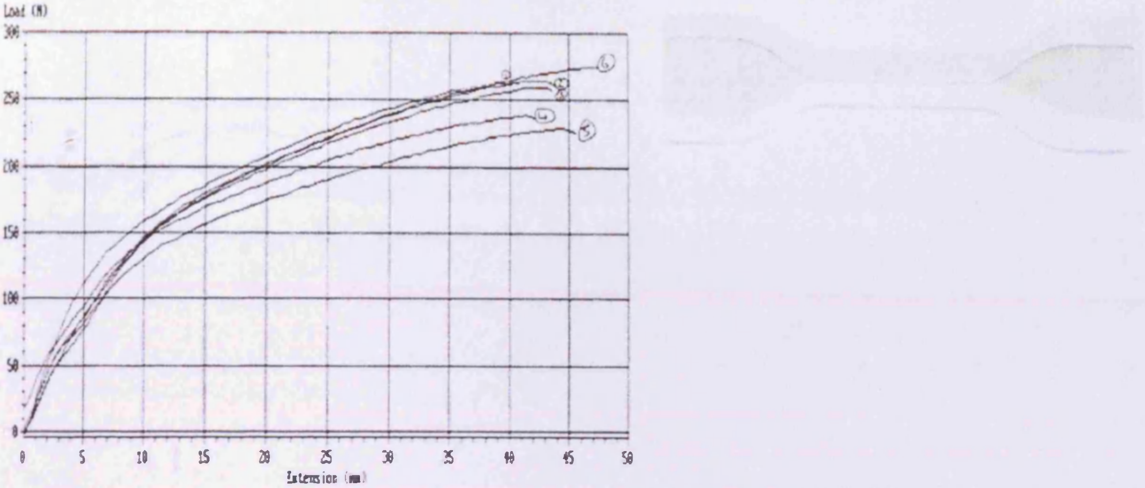
(a) tensile test results (b) specimen image

FIGURE H41 : 12/08/03A MATERIAL: VIRGIN LDPE CLASS: PLUS 5% CLING FILM



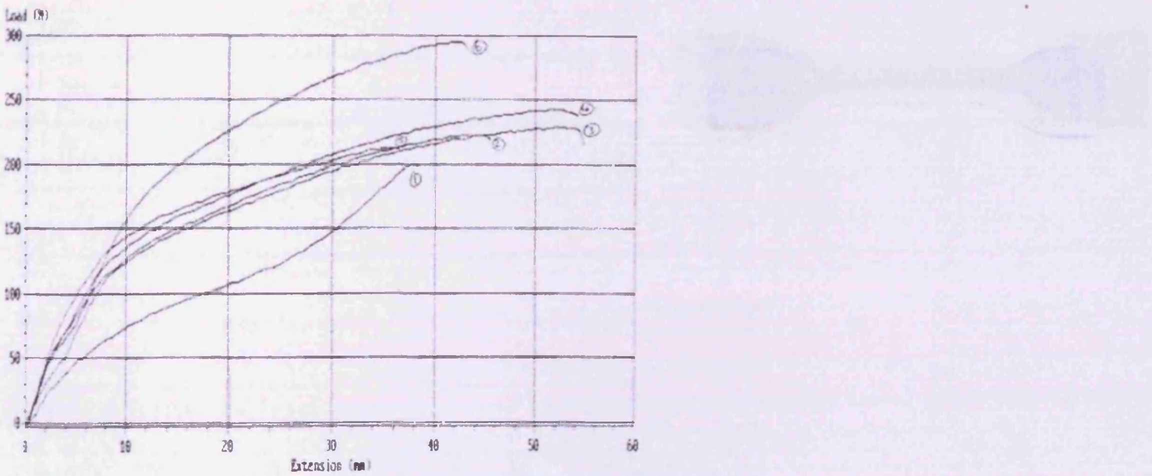
(a) tensile test results (b) specimen image

FIGURE H42 : 28/08/03 MATERIAL: VIRGIN LDPE CLASS: PLUS 10% CLING FILM



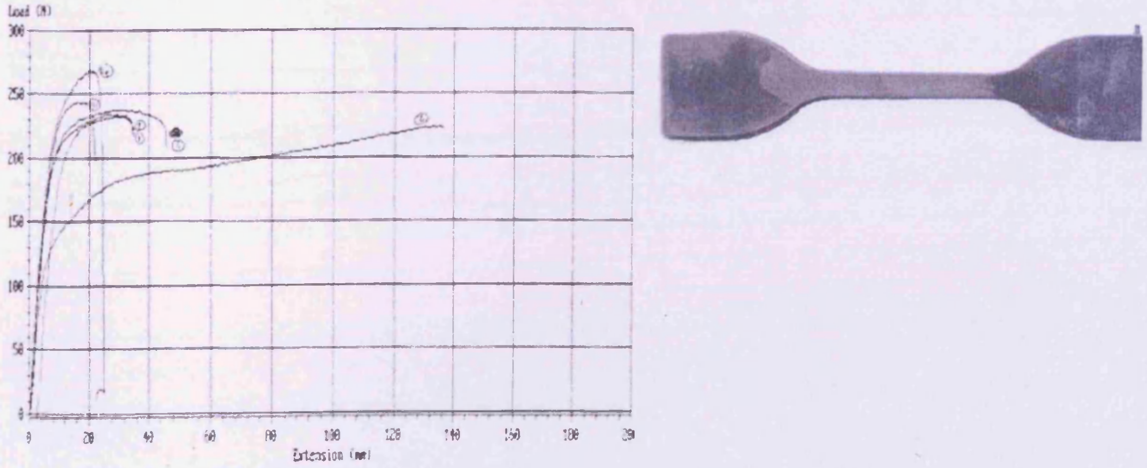
(a) tensile test results (b) specimen image

FIGURE H43 : 28/08/03A MATERIAL: VIRGIN LDPE CLASS: PLUS 15% CLING FILM



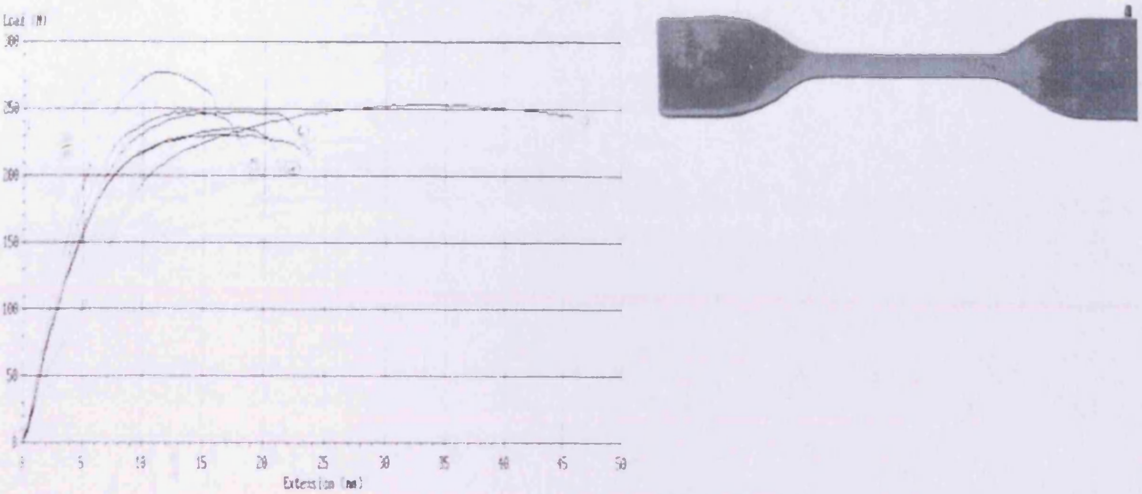
(a) tensile test results (b) specimen image

FIGURE H44 : 28/08/03B MATERIAL: VIRGIN LDPE CLASS: PLUS 20% CLING FILM



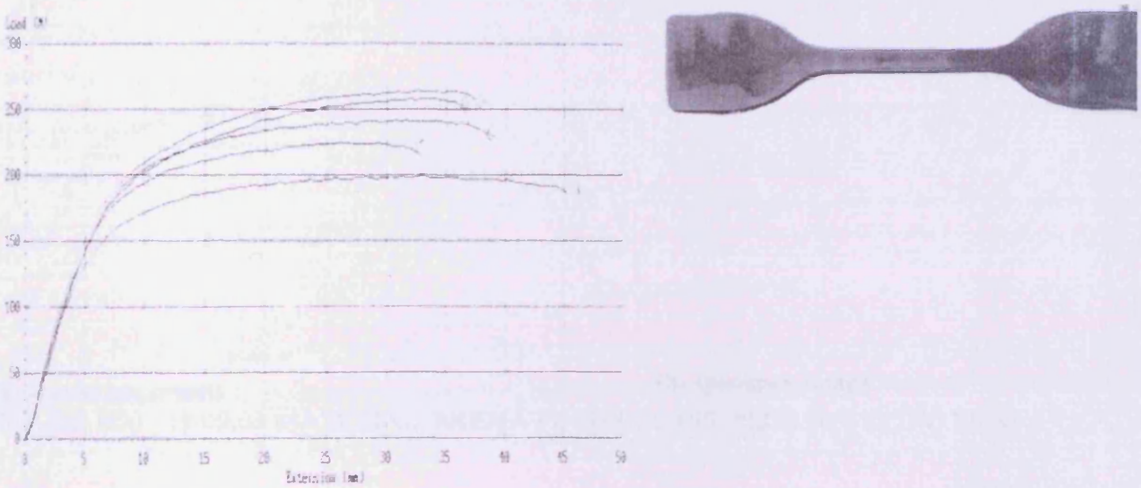
(a) tensile test results (b) specimen image

FIGURE H45 : 08/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 5% CLING FILM



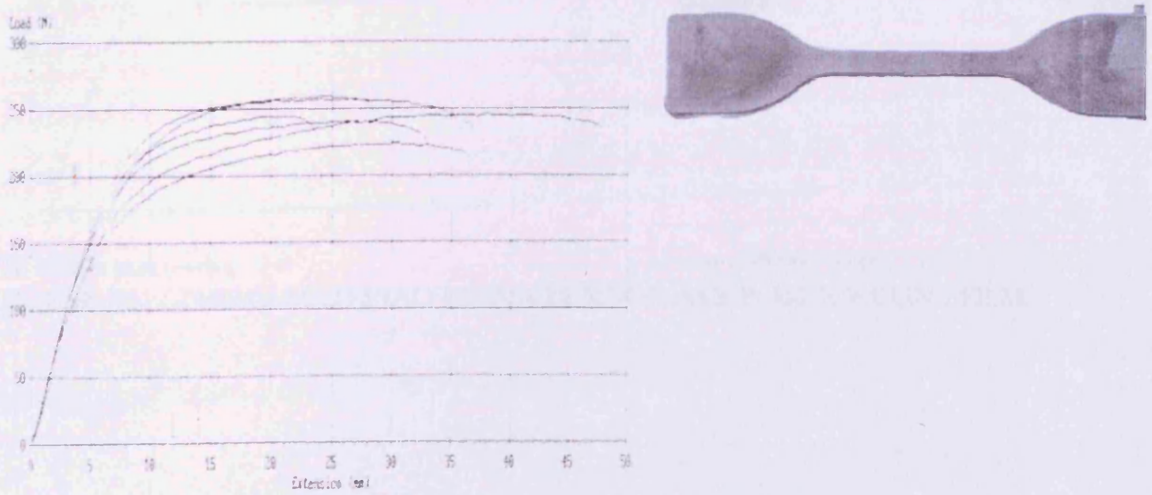
(a) tensile test results (b) specimen image

FIGURE H46 : 15/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 10% CLING FILM



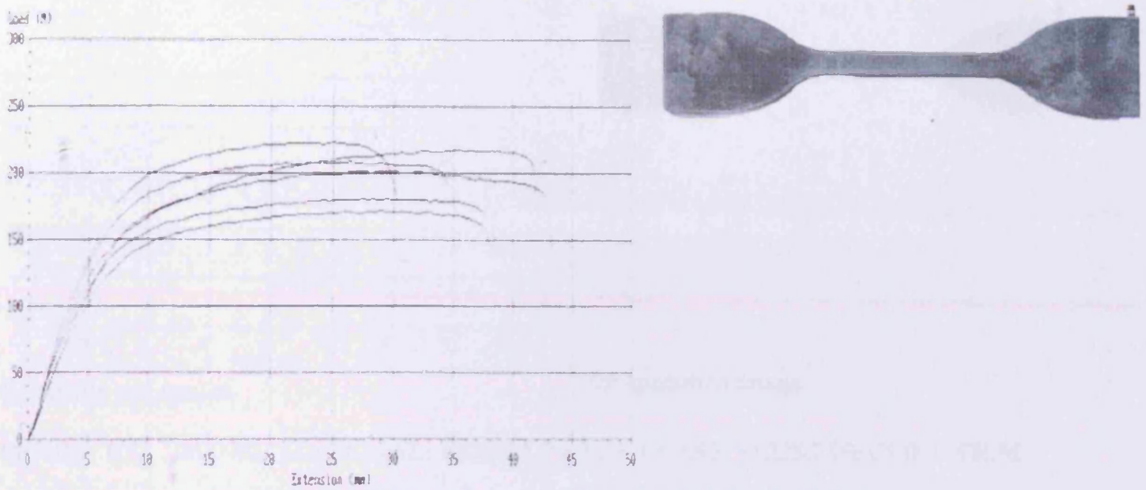
(a) tensile test results (b) specimen image

FIGURE H47 : 15/09/03A MATERIAL: EREMA PE MIX CLASS: PLUS 15% CLING FILM



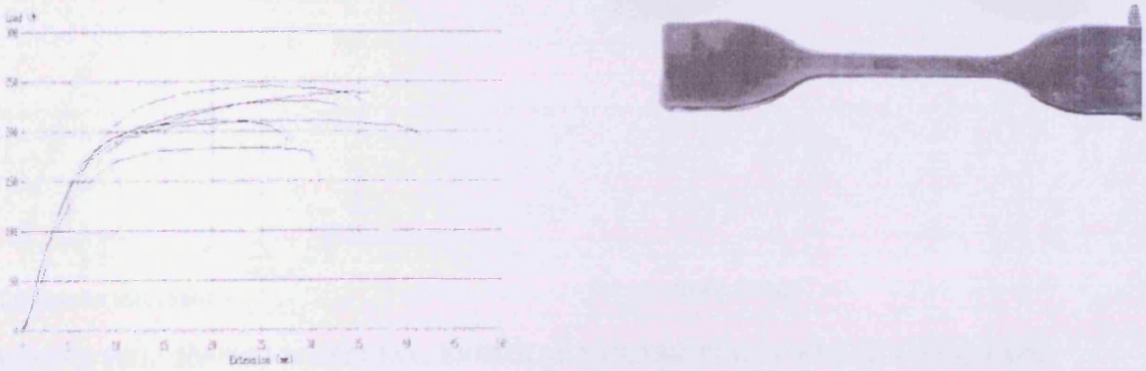
(a) tensile test results (b) specimen image

FIGURE H48 : 17/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 20% CLING FILM



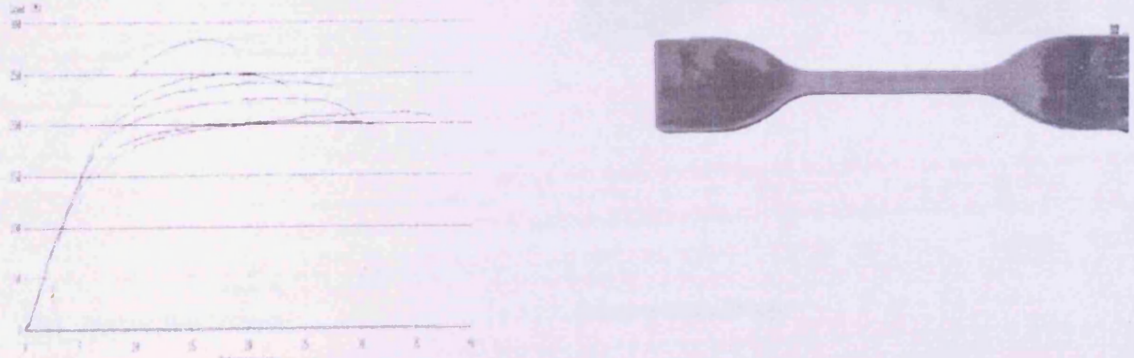
(a) tensile test results (b) specimen image

FIGURE H49 : 17/09/03A MATERIAL: EREMA PE MIX CLASS: PLUS 25% CLING FILM



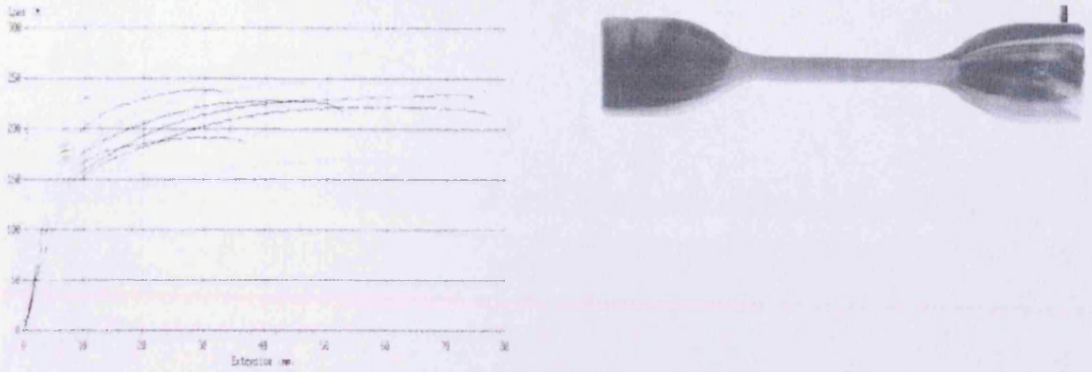
(a) tensile test results (b) specimen image

FIGURE H50 : 19/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 30% CLING FILM



(a) tensile test results (b) specimen image

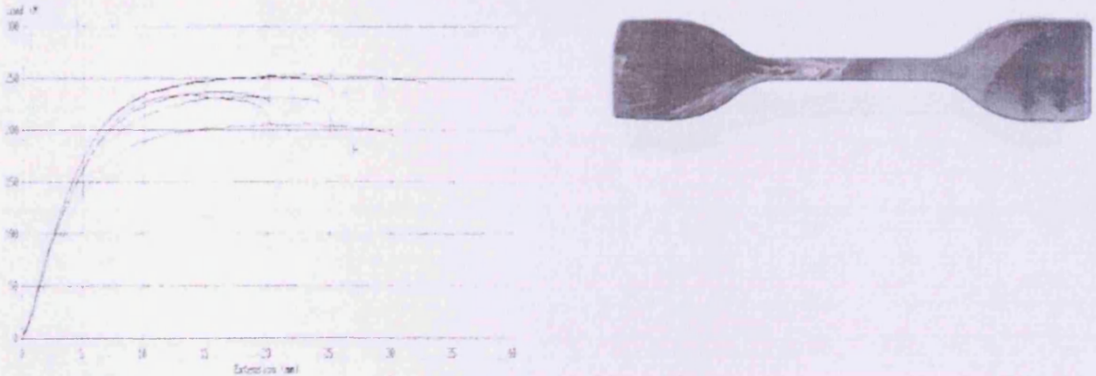
FIGURE H51 : 24/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 50% CLING FILM



(a) tensile test results

(b) specimen image

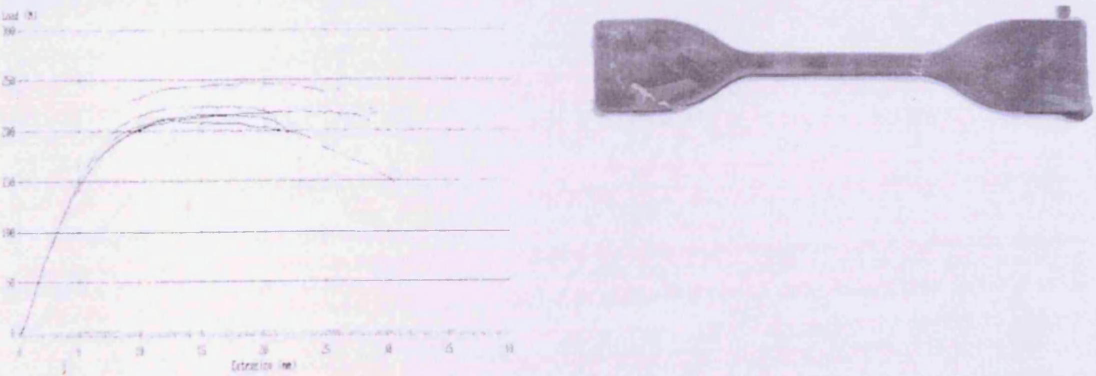
FIGURE H52 : 26/09/03 MATERIAL: EREMA PE MIX CLASS: PLUS 75% CLING FILM



(a) tensile test results

(b) specimen image

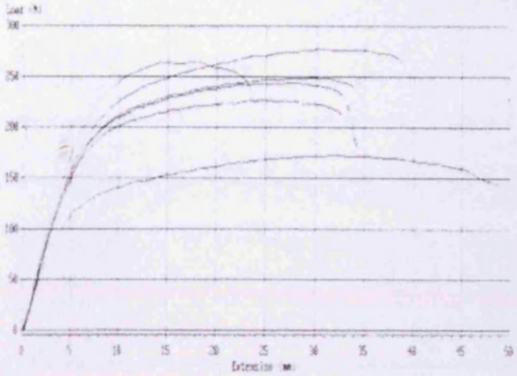
FIGURE H53 : 30/09/03 MATERIAL: EREMA MIX CLASS: PLUS 1% PACKAGING TAPE



(a) tensile test results

(b) specimen image

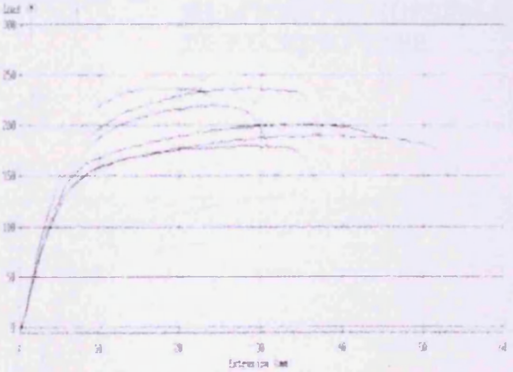
FIGURE H54 : 30/09/03A MATERIAL: EREMA MIX CLASS: PLUS 2% PACKAGING TAPE



(no image)

(a) tensile test results

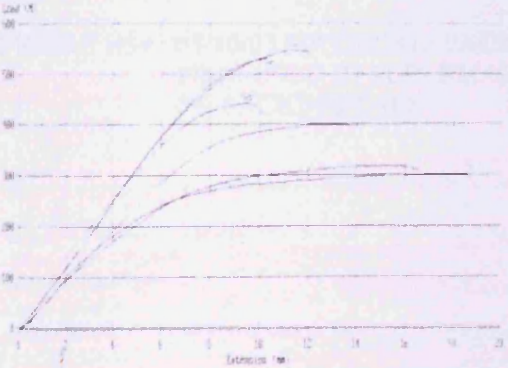
FIGURE H55 : 01/10/03 MATERIAL: EREMA MIX CLASS: PLUS 4% PACKAGING TAPE

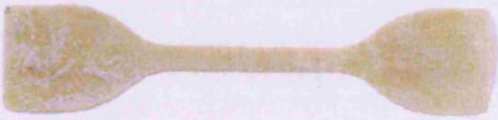


(a) tensile test results

(b) specimen image

FIGURE H56 : 01/10/03A MATERIAL: EREMA MIX CLASS: PLUS 6% PACKAGING TAPE

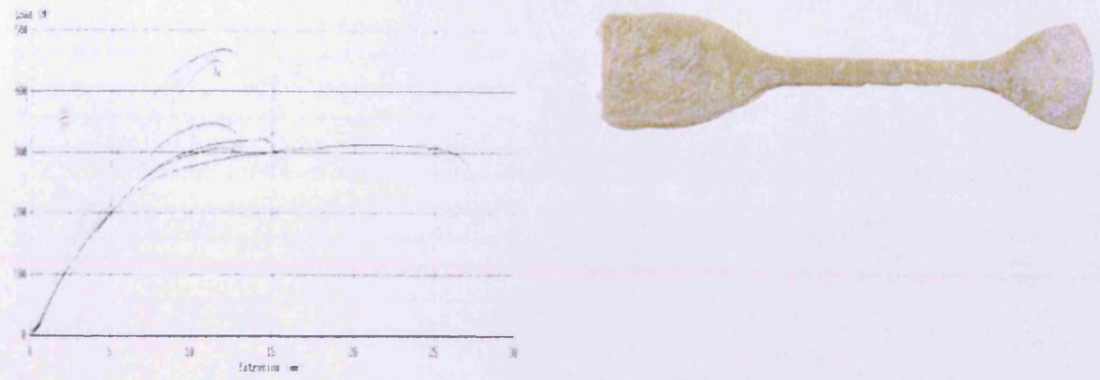




(a) tensile test results

(b) specimen image

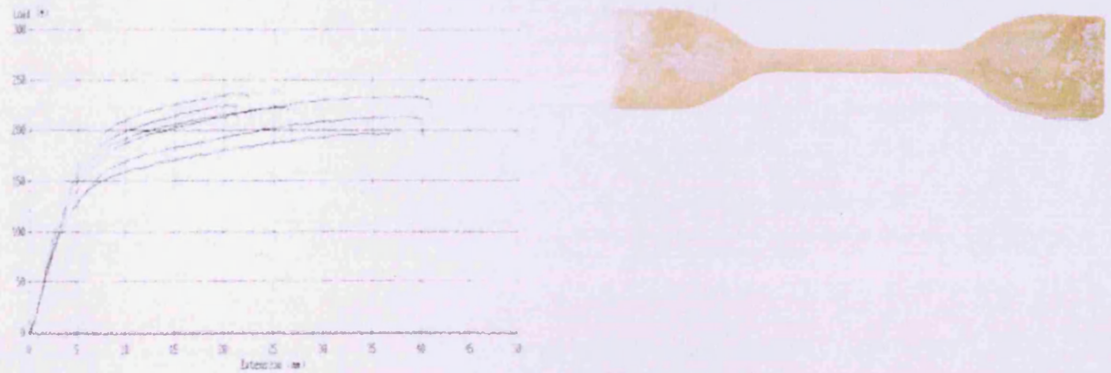
FIGURE H57 : 02/10/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 4% PACKING TAPE



(a) tensile test results

(b) specimen image

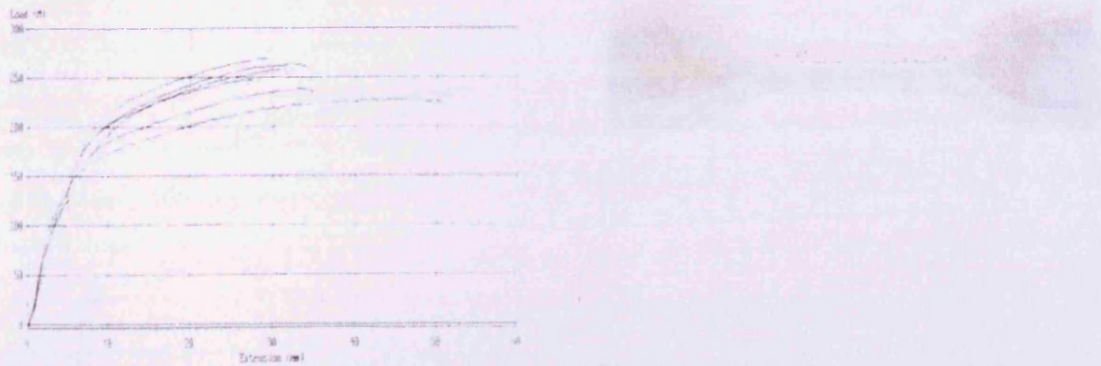
FIGURE H58 : 02/10/03A MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 2% PACKING TAPE



(a) tensile test results

(b) specimen image

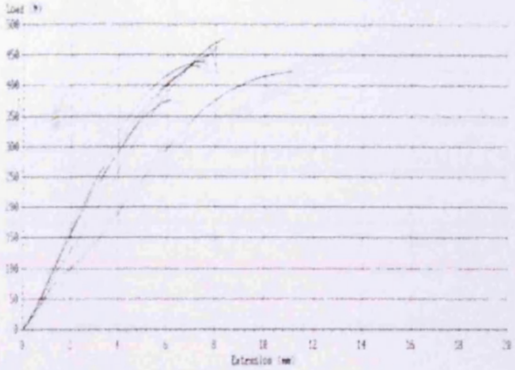
FIGURE H59 : 03/10/03 MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 6% PACKING TAPE



(a) tensile test results

(b) specimen image

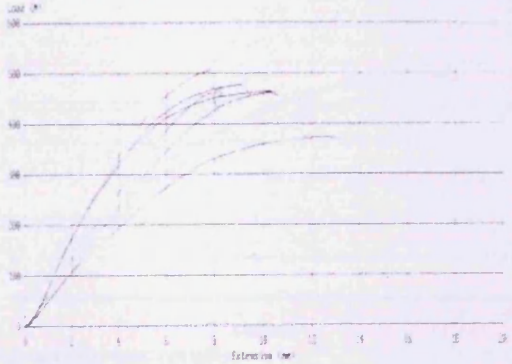
FIGURE H60 : 03/10/03A MATERIAL: PACKAGING LDPE CLASS: WRAPPING AND PACKING FILM USED IN SUPERMARKET WAREHOUSE. RECOVERED POST-USE. PLUS 1% PACKING TAPE



(no image)

(a) tensile test results

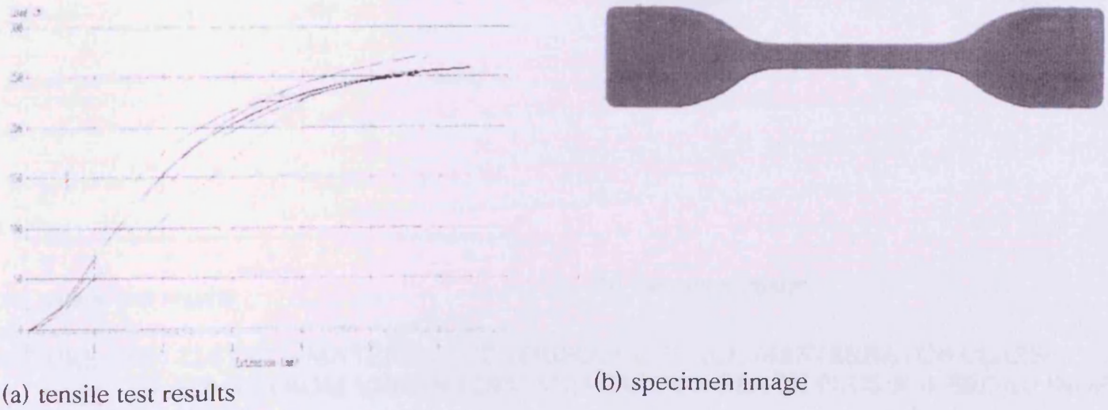
FIGURE H61 : 07/10/03 MATERIAL: DURHAM MBT RECOVERED FILM CLASS: FILM FROM MECHANICAL-BIOLOGICAL TREATMENT PLANT. PARTIALLY CLEANED AND FLOATED PROTION. NO FURTHER CLEANING DONE.



(no image)

(a) tensile test results

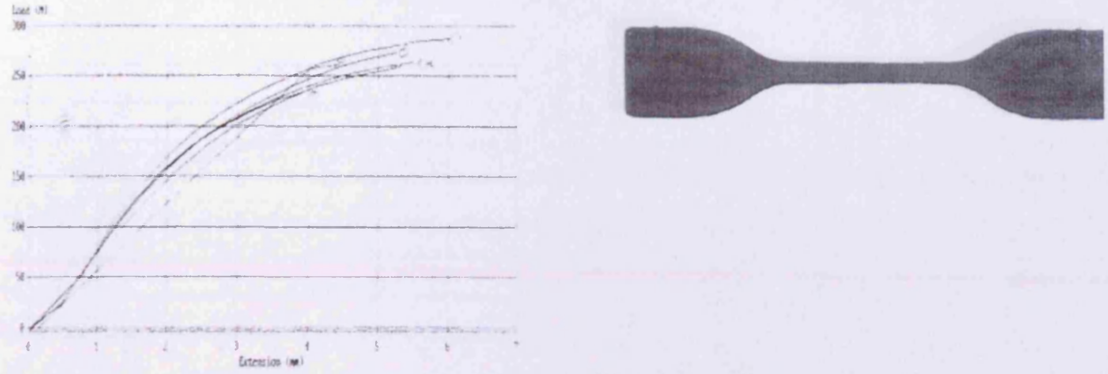
FIGURE H62 : 13/10/03 MATERIAL: DURHAM MBT RECOVERED FILM CLASS:FILM FROM MECHANICAL-BIOLOGICAL TREATMENT PLANT. PARTIALLY CLEANED AND FLOATED PROTION FOLLOWED BY 1 ½ HOURS WASHING IN SOAPY WATER. DRIED AT 80°C FOR 3 HOURS.



(a) tensile test results

(b) specimen image

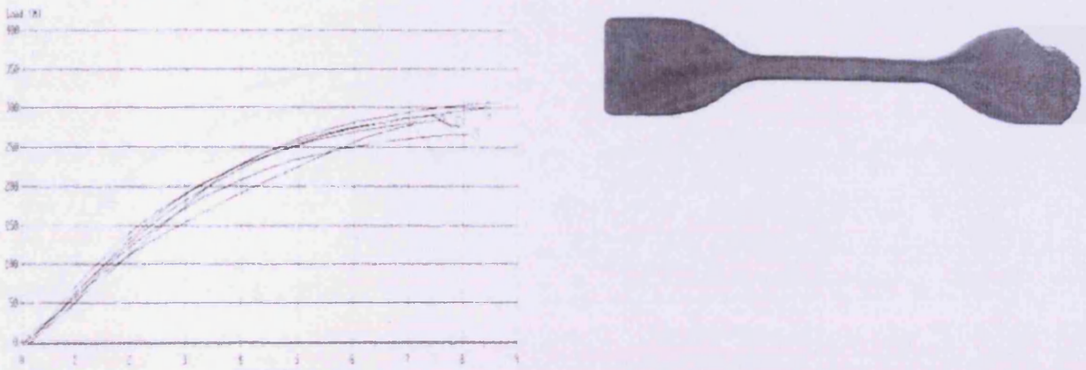
FIGURE H63 : 07/11/03 MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK



(a) tensile test results

(b) specimen image

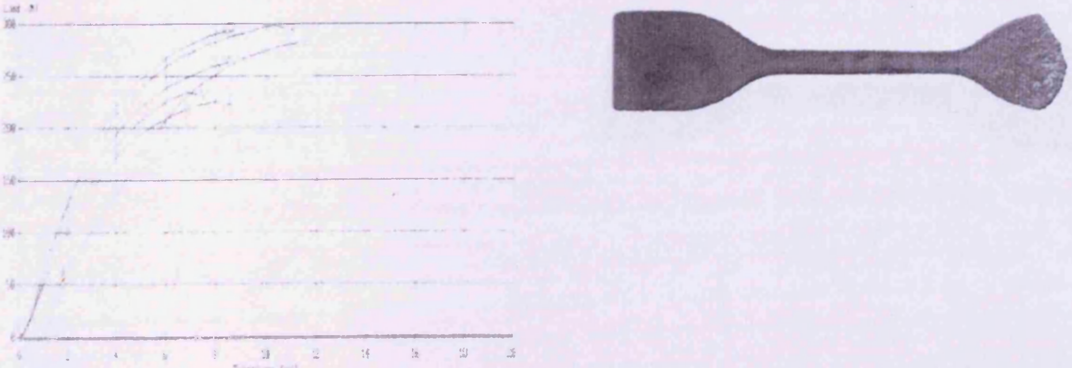
FIGURE H64 : 11/11/03 MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 10% BROAD INDEX LDPE.



(a) tensile test results

(b) specimen image

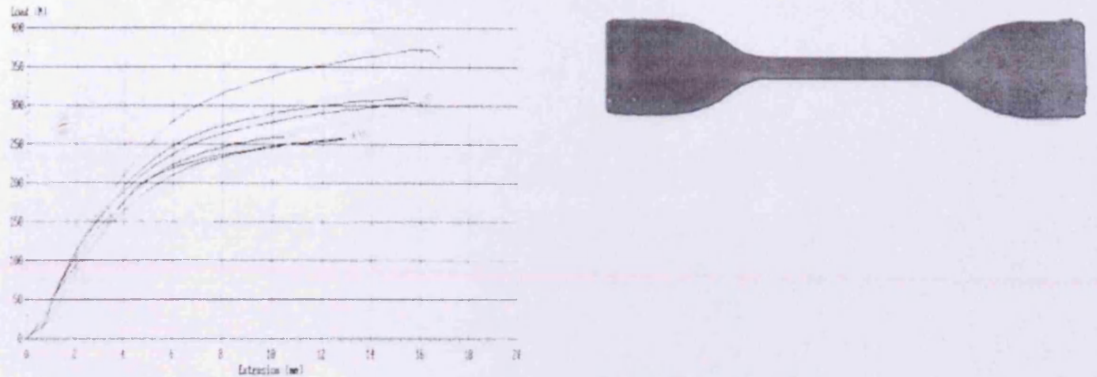
FIGURE H65 : 12/11/03 MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 20% BROAD INDEX LDPE.



(a) tensile test results

(b) specimen image

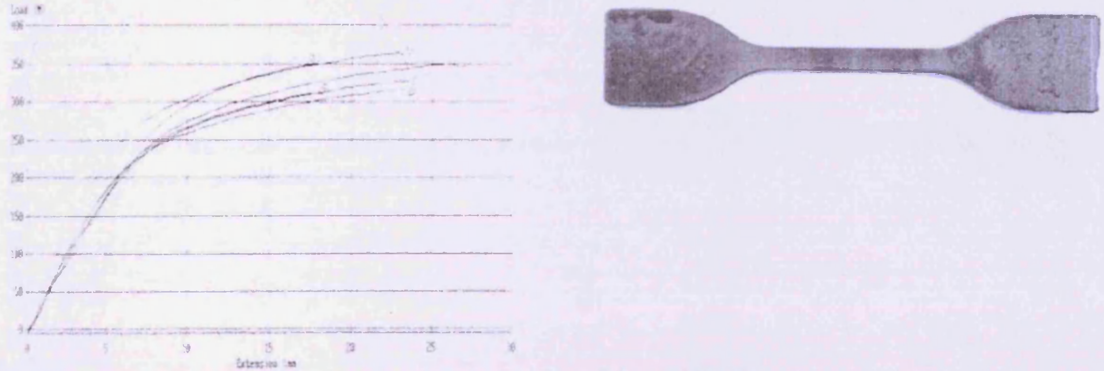
FIGURE H66 : 12/11/03A MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 30% BROAD INDEX LDPE.



(a) tensile test results

(b) specimen image

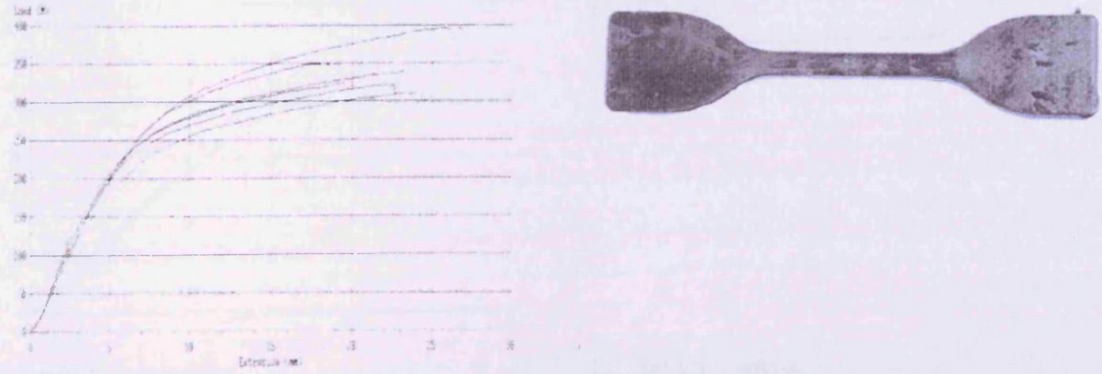
FIGURE H67 : 13/11/03 MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 50% BROAD INDEX LDPE.



(a) tensile test results

(b) specimen image

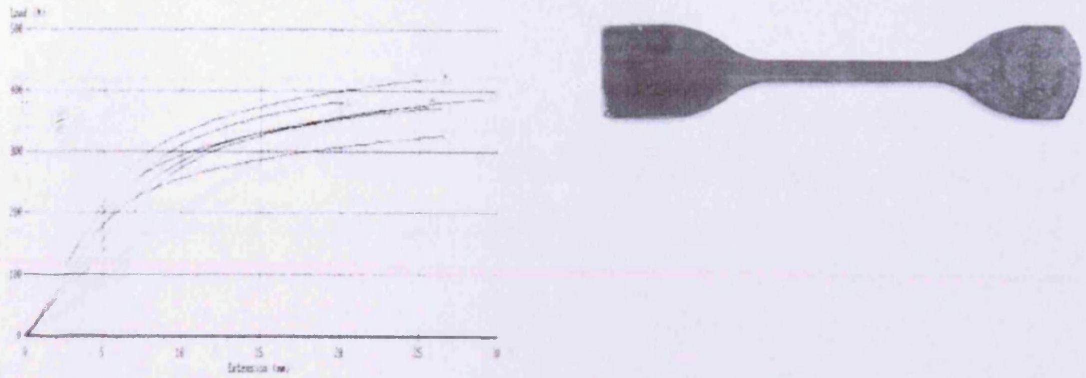
FIGURE H68 : 13/11/03A MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 70% BROAD INDEX LDPE.



(a) tensile test results

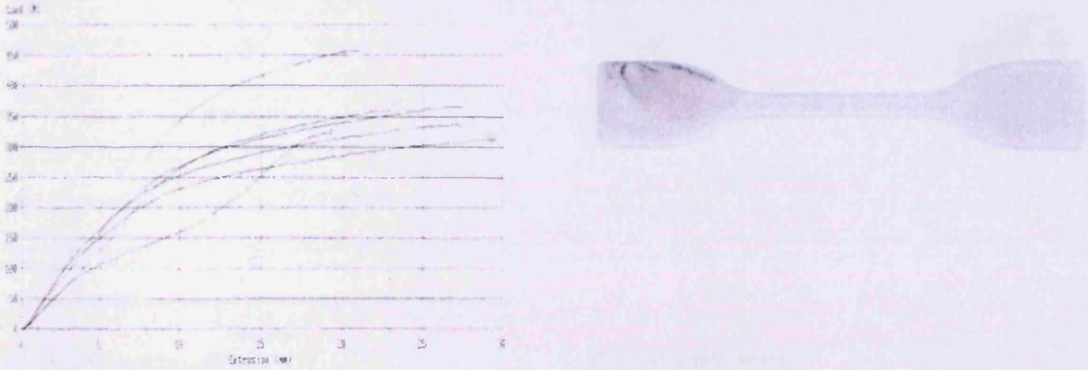
(b) specimen image

FIGURE H69 : 17/11/03 MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 80% BROAD INDEX LDPE.



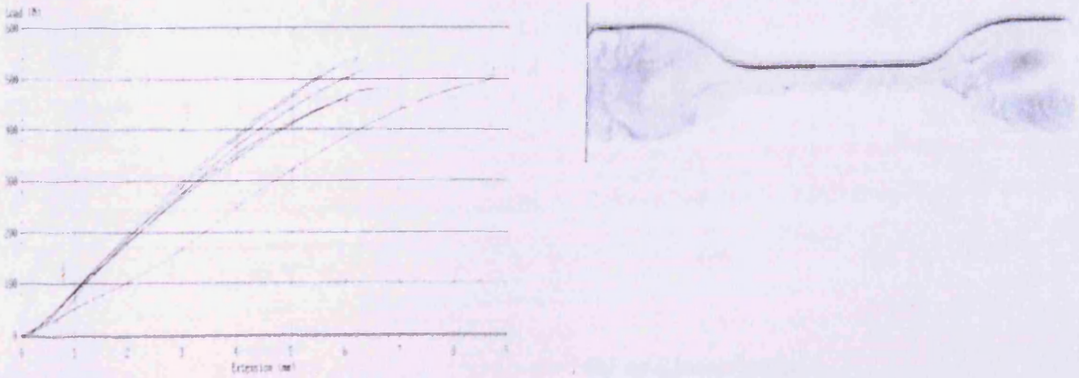
(a) tensile test results (b) specimen image

FIGURE H70 : 17/11/03A MATERIAL: CENTRIFORCE BLACK MASTERBATCH CLASS: MADE FROM VIRGIN LDPE AND CARBON BLACK PLUS 90% BROAD INDEX LDPE.



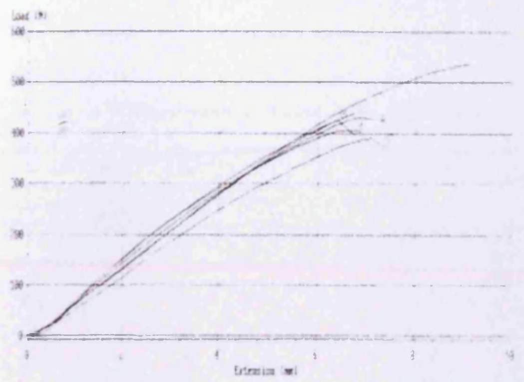
(a) tensile test results (b) specimen image

FIGURE H71 : 17/11/03B MATERIAL: 100% BROAD INDEX LDPE.



(a) tensile test results (b) specimen image

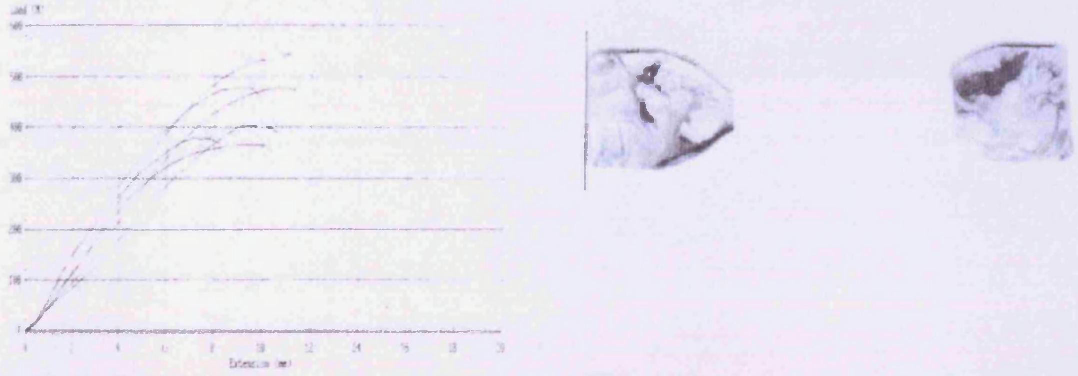
FIGURE H72 : 20/11/03 MATERIAL: 80% CARRIER BAG MATERIAL CLASS: PLUS 20% EREMA PE MIX



(no image)

(a) tensile test results

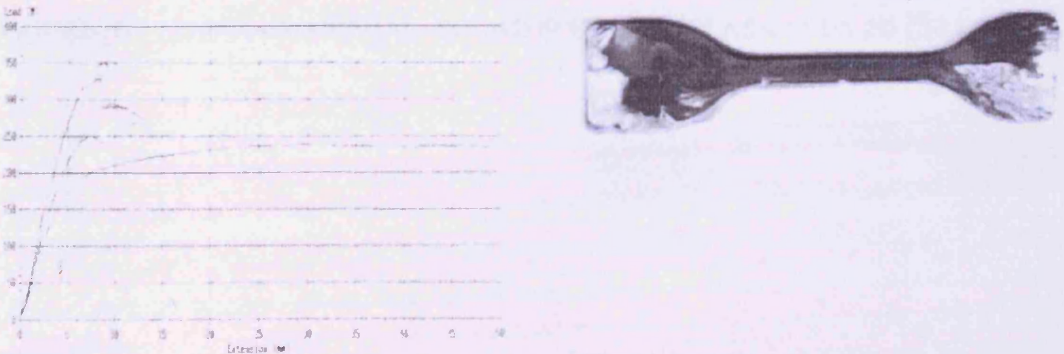
FIGURE H73 : 20/11/03A MATERIAL: 60% CARRIER BAG MATERIAL CLASS: PLUS 40% EREMA PE MIX



(a) tensile test results

(b) specimen image

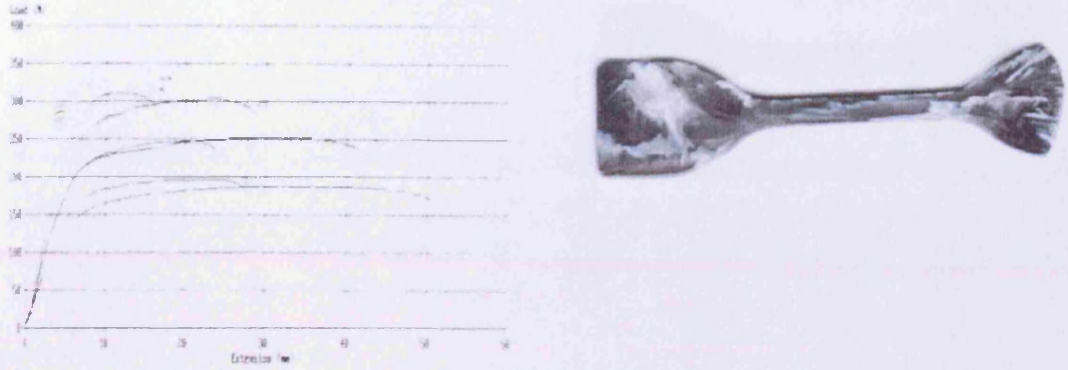
FIGURE H74 : 21/11/03 MATERIAL: 40% CARRIER BAG MATERIAL CLASS: PLUS 60% EREMA PE MIX



(b) specimen image

(a) tensile test results

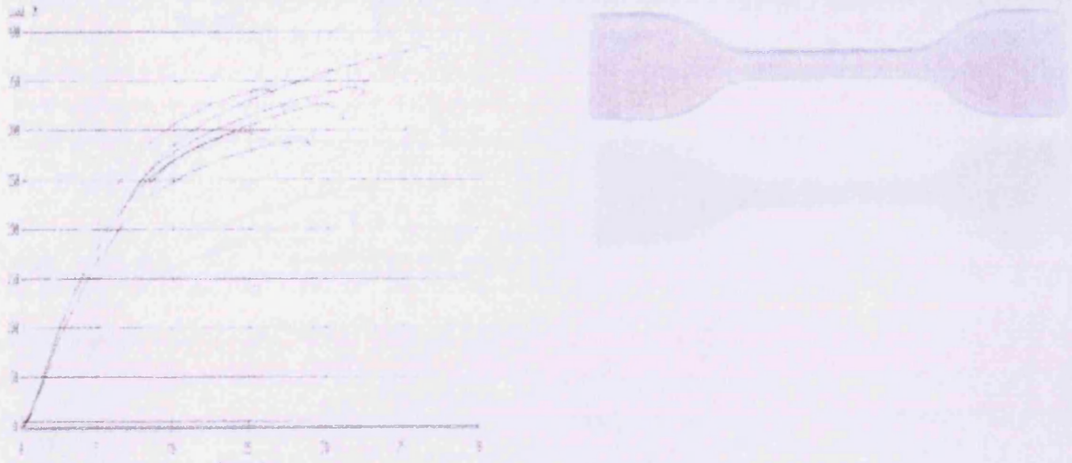
FIGURE H75 : 21/11/03A MATERIAL: 20% CARRIER BAG MATERIAL CLASS: PLUS 80% EREMA PE MIX



(a) tensile test results

(b) specimen image

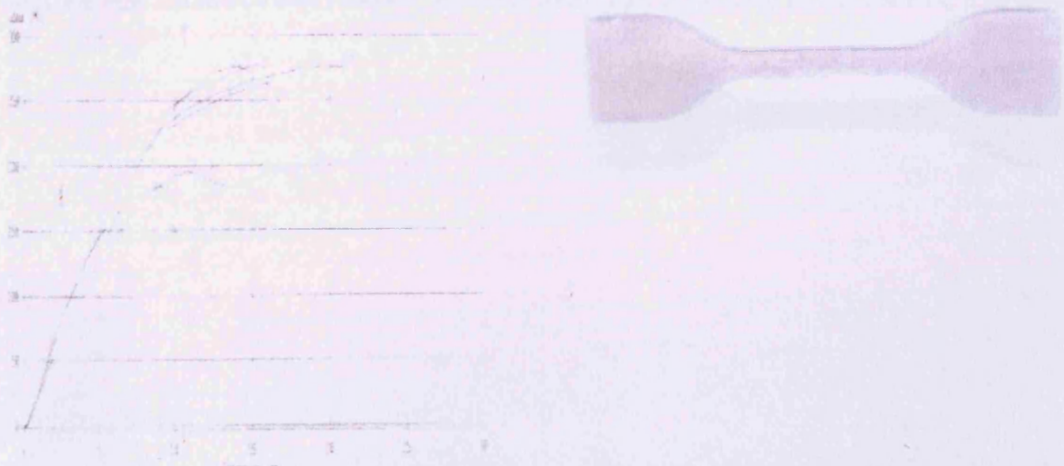
FIGURE H76 : 21/11/03B MATERIAL: 10% CARRIER BAG MATERIAL CLASS: PLUS 90% EREMA PE MIX



(a) tensile test results

(b) specimen image

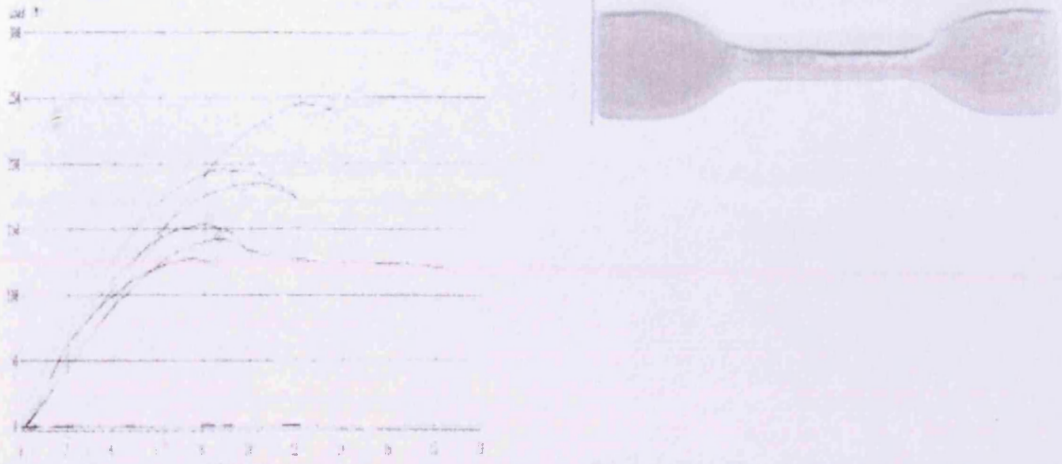
FIGURE H77 : 29/04/04 MATERIAL: BROAD SPEC LDPE CLASS: PLUS 2% CELLULOSE TAPE



(a) tensile test results

(b) specimen image

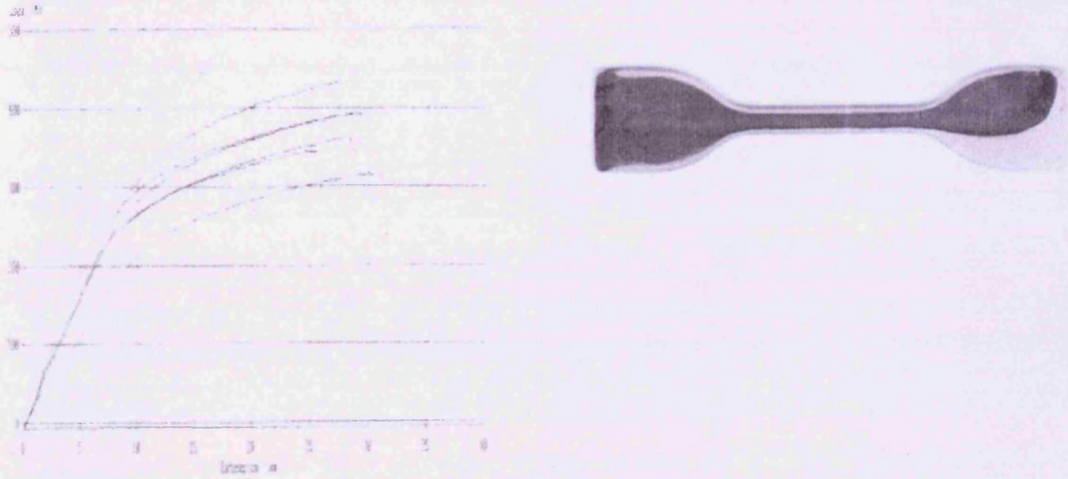
FIGURE H78 : 29/04/04A MATERIAL: BROAD SPEC LDPE CLASS: PLUS 4% CELLULOSE TAPE



(a) tensile test results

(b) specimen image

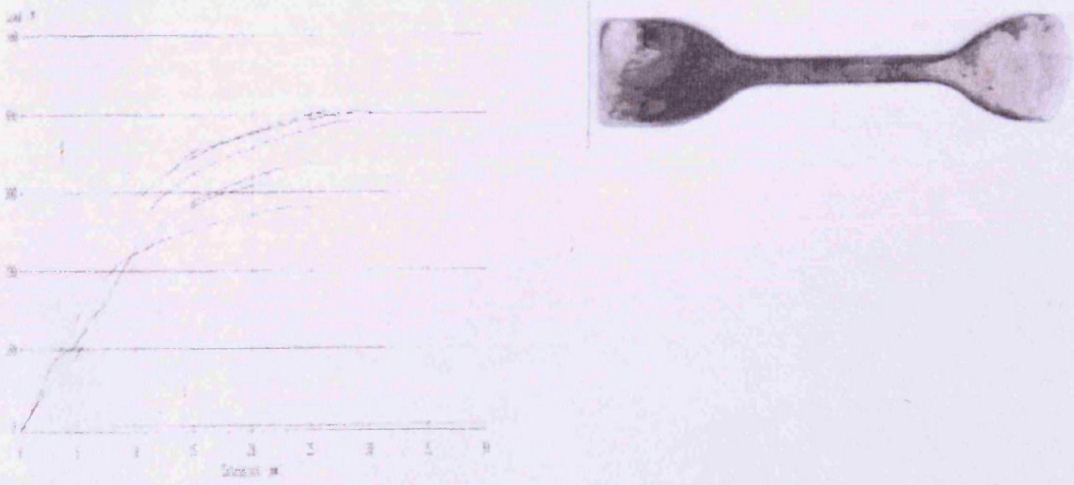
FIGURE H79 : 29/04/04B MATERIAL: BROAD SPEC LDPE CLASS: PLUS 6% CELLULOSE TAPE



(a) tensile test results

(b) specimen image

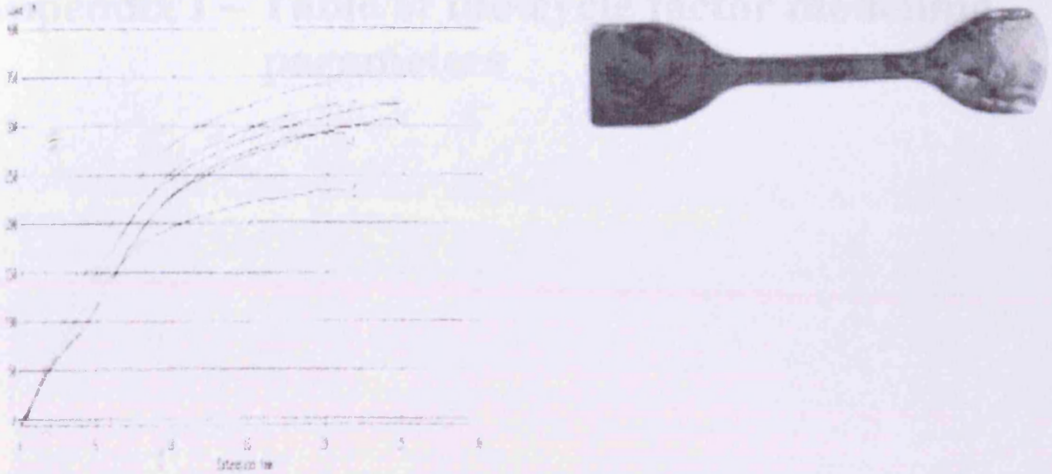
FIGURE H80 : 30/04/04 MATERIAL: BROAD SPEC LDPE CLASS: PLUS 2% PVC TAPE



(a) tensile test results

(b) specimen image

FIGURE H81 : 30/04/04A MATERIAL: BROAD SPEC LDPE CLASS: PLUS 4% PVC TAPE



(a) tensile test results (b) specimen image

FIGURE H82 : 30/04/04B MATERIAL: BROAD SPEC LDPE CLASS: PLUS 6% PVC TAPE

# Appendix I – Table of life-cycle factor modelling parameters

Table I1: Life cycle factors and their effect on crystallinity.

| Factor | Parameter | Effect on crystallinity |
|---|---|---|
| Heat cycling – Low density Polyethylenes | Per heat cycle | Increase 3.6% |
| Heat cycling – Medium density Polyethylenes | Per heat cycle | Increase 1% |
| Heat cycling – High density Polyethylenes | Per heat cycle | Decrease 1% |
| Dirt contamination | Per 1% dirt | Increase 5% |
| Tape contamination - PP | Per 1% tape | Increase 1% |
| Tape contamination – PVC | Per 1% tape | Increase 1% |
| Tape contamination – Cellulose | Per 1% tape | Decrease 1% |

# Appendix J – Economic model program code

```
Sub Macro1()
'
' Macro1 Macro
' Macro recorded 13/04/2004 by scerm


'Varying recovered portion with gate fee

For i = 1 To 100

For j = 1 To 10

a = Trim(Chr(j + 65)) + Trim(Str(i))
cl = "A" + Trim(Str(i))
rw = Trim(Chr(j + 65)) & 1


        Sheets("Inputs").Select
        Range("B4").Select
        ActiveCell.FormulaR1C1 = i

        Sheets("Inputs").Select
        Range("F19").Select
        ActiveCell.FormulaR1C1 = (10 * j - 60)

        Sheets("Net economics").Select
        cval = Range("B13")

        Sheets("calcs").Select
        Range(a).Select
        ActiveCell.FormulaR1C1 = cval

        Range(cl).Select
        ActiveCell.FormulaR1C1 = i

        Range(rw).Select
        ActiveCell.FormulaR1C1 = j * 10 - 60

Next j

   Next i


End Sub
Sub Macro6()
'
' Macro6 Macro
' Macro recorded 13/04/2004 by scerm
'
```

```
'
    Sheets("Inputs").Select
    Range("B4").Select
    ActiveCell.FormulaR1C1 = "100"
    Range("B5").Select
End Sub
```