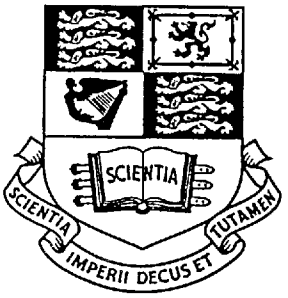
IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE



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Limits to Plastics Recycling in the Developing and Developed Economy

by

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Dedicated to my beloved

Father, Mother* and *Mother-in-law

with everlasting affection and honour

who missed me so much during this project

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FOREWORD

This Ph.D. project in the subject of Environmental Technology represents a unique attempt to study the limitations in mechanical recycling of plastics waste in the developing economy in comparison to those in the developed economy through combining and sharing a substantial amount of geographical, environmental and polymeric knowledge, experiences and experimental results.

However, the pressures and opportunities for recycling of plastics in the developed economy differ from those in the developing economy. It is interesting to note that the economics of the recycling is inversely related to the level of economic development, unless and until the innovation of an economically viable recycling strategy and technology occurs in the developed world. Therefore, in more general terms, propensity to recycle the waste is also found to have an inverse relationship with the socio-economic status of countries. Although, facilities for reprocessing plastic wastes under known processing conditions are available in the developed nations, these wastes are generally recycled several times under unknown processing conditions combined with cumulative effects of extraneous contaminants in developing countries. These contaminants add inevitably into reclaimed plastic feedstocks during each cycle of successive recyclings. The deleterious effects experienced by the plastic materials occur either during their repeated processings at different recycling cycles or their service lifetime.

Therefore, it is postulated here that the limits to recycling plastics in terms of a maximum number of times differ with the socio-economic situation of a country. It is strongly believed that this timely study has focused an important environmental and geographical problem at the current stage of the world's economic development.

Author

ABSTRACT

Plastic waste recycling is not just an activity developed under environmental pressure, rather it has been inspired by a number of economic and social reasons especially in some of the developing countries, e.g. Bangladesh and India. Contrary to UK cities, mechanical recycling for post-user plastics in Dhaka, Calcutta and Delhi is widespread, and carried out under an informal sector, with highly significant economic and social implications for the citizens. The existing barriers and future potential difficulties at different levels of economic progress are described.

Nevertheless, the uncertainty related to polymeric properties' degradation over the course of successive recyclings has important concerns in both parts of the world. It was hypothesised that, depending on the rate and nature of the degradation, recycled plastic materials will become useless at an earlier stage in the case of closed-loop recycling system of the developing world than the open-loop system of the developed world. Some of the mechanical and rheological properties of a total of 15 different batches of High Density Polyethylene general scraps were determined against their successive numbers of times processed previously in Dhaka, Calcutta and Delhi. A catastrophic fall occurred in the 'stress at yield' and 'strain at break' properties of the batches processed previously more than 6 times, along with a steady decrease and a small increase in their 'stress at break' and 'melt flow rate', respectively. The results for virgin HDPE reprocessed in-house up to 15 times under known processing conditions also indicates that a substantial drop in mechanical properties occurred after around 4-5 number of processings.

Future scenarios of closed-loop plastics recycling in Bangladesh are determined through developing some mathematical models, in order to test the hypothesis proposed in this study. Consequences related to these scenarios are discussed. A comparative study has also been carried out from a UK perspective, representing the developed economy, through literature research and a questionnaire survey. Finally, recommendations for future study are made.

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4/	Milky coloured rod pellets,	(4)/Pro-3;
5/	Brown coloured granules,	(5)/Pro-4,5;
6/	Dull brown coloured granules,	(6)/Pro-6,7;
7/	Black coloured granules,	(7)/Pro-8,9;
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SYMBOLS, ACRONYMS AND ABBREVIATIONS USED IN THE TEXT

s = second
min = minute

lb = pound
1 lb ≈ 0.45 kg
1 ounce ≈ 31.1 g
g = gram
kg = kilogram
M = million
Mkg = mega or million kilogram
1 ton = 1.016 tonne
1 tonne = 1000 kg
ktonnes = kilo tonnes (= 1000 kg)
bn = billion (10^9)

mm = millimetre
mm/mm = millimetre per millimetre
cm = centimetre
m = metre

±SE = plus and minus standard error
CV = coefficient of variation
SD = standard deviation
NS = not significant at $p<0.05$
p = level of significance

N = newton (= kg m s^{-2})
kN = kilo Newton
Nm^{-2} = Newton per square metre
Pa = pascal (= N m^{-2})
psi = pounds per square inch (= 6895 Nm^{-2})
MPa = mega pascal
J = joule (= N m)
kHz = kilo hertz (s^{-2})

rpm = revolutions per minute

MFR = melt flow rate
^{0}C = degree centigrade
mw = molecular weight

Sl.No. = serial number
TK. = Taka - Bangladesh currency
(US$ 1 = TK. 41.5 on April 1996)

Pro 0 = processed zero or never processed
Pro 1 = processed once;
Pro 2 = processed twice (and so on)

PE = polyethylene
LDPE = low density PE
LLDPE = linear low density PE
HDPE = high density PE
PP = polypropylene
PS = polystyrene
PVC = polyvinyl chloride
PVA = polyvinyl acitate
PET = polyethylene teraphthalate
ABS = acrylonitrile-butadiene-styrene

MSW = municipal solid waste.
GDP = gross domestic production
APME = Association of Plastics manufacturers in Europe (Brussels, Belgium).
IPTS = Institute of Prospective Technology Studies (European Commission, Seville, Spain).
APC = American Plastics Council (Washington, USA).
VKE = German Association of the Plastics Producing Industry.
DSD = Duales System Deutschland, Germany.
PRG = Producer Responsibility Group, UK.
VALUPLAST = Materials organisation for plastics, UK.
VALPAK = A newly formed "collective" scheme, UK.

NTP = number of times processed
II = import intercept
RI = recovery intercepts
LI = landfill intercepts
EDP = extended data points
IEDP = imports extended data points
REDP = recovery extended data points
LEDP = landfill extended data points
LgNSP = legislative limit for number of successive of processings

CHAPTER 1:

Introduction

1.1 The Study Problem

Plastic waste collection, separation and recycling in developing countries present a socio-economically and technologically very different picture from that in advanced countries. Table 1.1 shows that countries in the developing economy such as Bangladesh and India, have a low per capita plastic consumption and waste generation coupled with higher rates of reuse and recycling (Haque, 1994; Haque et al, 1997; Haque and Bell, 1998; Giri and De, 1992; Kundu, 1994; Ganguli, 1995), while the reverse occurs in the economically developed countries (APME, 1997). Thus, in the UK and elsewhere in the western world, the per capita plastics consumption and waste generation are very high but there are remarkably low rates of reuse and recycling (Table 1.1), with most waste currently being incinerated or buried in landfill (BPF, 1979; PRF and CPRR, 1992; Radar and Stockel, 1995; Ogilvie, 1996; BPF, 1996; APME, 1997). However, although the pressures and opportunities for mechanical recycling of plastics in the developed economy (DoE and WO, 1995; Ogilvie, 1996) differ from that in the developing economy, the long-term future of its recycling in both parts of the world must be viewed with some uncertainty, which has important implications for both types of economy.

Table 1.1: Mechanical recycling of post-user plastic waste by country / region.
(1 tone = 1.016 tonnes)

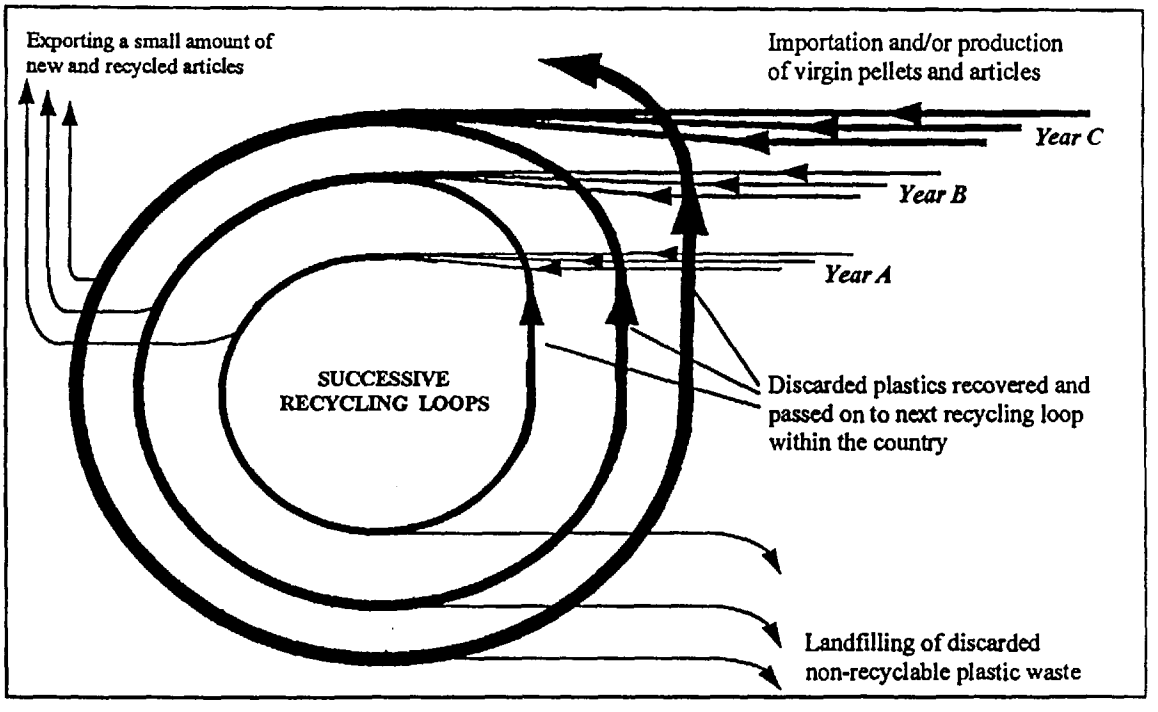
Country / Region	Post-user plastic waste generated locally [Units: x 1000 tonnes / year]	Amount recycled mechanically
Bangladesh[1]	**12**	**95 to 98 %**
India[2]	**300**	**60 to 80 %**
Austria[3]	279	15.3 %
Switzerland[3]	342	11.9 %
Germany[3]	3,181	10.9 %
Netherlands[3]	847	7.9 %
UK[3]	2,193	4.6 %
France[3]	2,997	4.4 %
Western Europe[3]	16,313	7.6 %

Data sources: [1] Haque, 1994; [2] Ratra, 1994 and Ganguli, 1995; [3]APME, 1997 (1995 Data).

One common but crucial problem for both economies is to define the *ultimate limit* for recycling plastics waste, in particular, how many times plastic waste can be recycled successively, after which recycled products will turn into useless materials due to quality degradation and thus have no market value. This limit of successive recyclings will vary depending on the relevant socio-economical, technical, environmental and legislative

factors involved in the context of developing and developed economy. The visual appearance of recycled products indicates that deterioration in the quality of plastic results from the recycling process itself, and it may be exacerbated if the plastic, even after cleaning and washing steps, remains contaminated. This is a common problem which occurs very often in the recycled products of developing countries (Haque, 1994; Ganguli, 1995). Under the current effectively closed-loop recycling system in Bangladesh and India (Figure 1.1), every year more material is coming into the system and being recycled following the manufacturing-marketing-consumption-discarding steps. Hence, the size of the *'recycling loop'* is expanding increasingly to accumulate additional materials into the system as shown in Figure 1.1. At the same time, effects of repeated processings will accumulate progressively in the properties of recycled plastics over the course of successive cycles. According to the rate and nature of the deleterious effects, the materials will deteriorate to a stage at which it can be postulated that they will not be suitable for further recycling.

Figure 1.1: Schematic diagram of closed-loop plastics recycling system in Bangladesh.



Consequently, at some point in the foreseeable future in developing country cities, such as Dhaka, Calcutta and Delhi, the existing crude landfilling may be one of a few available options for the disposal of those non-recyclable useless plastics. This is because of the fact

that plastics recycling systems in these cities involve successive processings of the waste under unknown/uncontrolled processing conditions, and a particular batch of feedstocks contains a higher percentage of extraneous particles including polymer parts of unknown grades such as mixed, other and/or the same type but degraded plastics.

In contrast, in the case of UK plastics recycling, it is probably reasonable to assume that quality deterioration in the mechanically recycled plastics will not be a vital problem if the recycling companies remain selective in terms of restricting their activities to the large, easily sortable and cleaned plastic waste streams. However, in order that the future of recycling is viable and progressive, within the framework of the Government's recycling targets (DoE, 1995), important aspects such as potential and foreseeable problems in long term operations must be considered before programmes are embarked upon. Although very few basic studies have been carried out to determine the effect of in-house successive reprocessings on the properties of known grade plastics, there appears to be no research of such a nature undertaken on 'general scrap plastics' previously recycled several times under the real conditions of the developing economy of Bangladesh and India.

The current research centres on developing some mathematical models for the future scenarios of mechanical recycling of post-consumer plastic waste (Chapter 6), through determining the effects of successive processings (Chapters 3, 4 and 5) and outlining all other factors governing the growth of recycling activities (Chapters 2 and 3). It is based on case studies of two countries from the developing economy - Bangladesh and India, and one country from the developed economy - the UK. Both the developing countries are identical in terms of their performance in plastics recycling and also in sharing locally developed recycling concepts, techniques and technology. In this respect, it is worth describing some background to the mechanical recycling of plastic waste in all these three case study countries.

1.2 Status of Plastic Waste in the Developing Economy

In most developing countries, particularly in Bangladesh and India, plastic waste has been recycled informally, using small scale and simple man-powered machines (Volger, 1985; Volger, 1986; Ahsan et al, 1992a; Haque, 1994). Bangladesh started recycling plastics in

the late 1960s, and by the beginning of the 1990s, a considerable improvement had been made in the waste recycling technology based on local resources (Haque and Bell, 1998). Currently Bangladesh appears to have one of the most efficient recycling systems in the world, driven by economic necessity associated with poverty (Ahsan, et al, 1991; Haque, 1994; Haque and Bell, 1998). As a result, close to 100% of recyclable plastic appears to be recycled, any material discarded presumably being too small or difficult to retrieve from the waste stream (Rahman, 1993; Haque, 1994). Therefore, the Dhaka landfill must contain only unrecoverable plastics. Rickshaws, rickshaw vans, carts and boats are used for the movement of the materials, including manual transport. Sometimes, trucks are used for inter-district transport if required. This whole system is also favoured by an unrestricted area for application of recycled plastic (Appendix 1.1) and a widespread market for articles manufactured from it in a country of a 111.4 million mostly poor illiterate people[1]. Superficially, all these facts indicate a very environmentally friendly system, but there are serious doubts over certain aspects in this respect, notably the quality degradation of the recycled products and its future implications which need to be addressed.

An almost similar pattern in all respects of plastic recycling is present in most of the Indian metropolises as observed in Dhaka, Calcutta and Delhi. Economic and social implications of this informal activity are also comparable. In this country, plastic recycling is also a self-organised sector sustained by a chain of self-employed waste pickers, traders, dealers, and reprocessors for whom this work is a source of income (Giri and De, 1992; Kundu, 1994, Ganguli, 1995). The basic contrast is that the size and scale of operation of the Indian Plastics Waste Industry is vast. Ganguli (1995) reported that over one million waste pickers and around 20,000 enterprises are involved in plastics recycling in this country. With their self-involvement with enterprising nature over the last three decades, the number of these industries has increased up from 2000 in 1987-88 in the towns and cities of the country, and they have become mature and well organised, involving themselves in recycling/reprocessing more than 323,209 tonnes of the waste per year (Ganguli, 1995; Ratra, 1994)

[1] Per capita GDP = US$ 126 in 1993-94; Literacy rate (for 7 years +) = 32.4% (BBS, 1996).

As in Bangladesh, plastics recycling activities and businesses are running profitably in the Indian economic context, and the major share in the waste collection in terms of both the quantity and value is accounted for by plastics (Ratra, 1994). In 1993-94, India's plastics production amounted to around 902,000 tonnes (up from a meagre 15,240 tonnes in 1960), and the demand of 1.21 million tonnes is expected to go up to 2.15 million tonnes by the year 2000 as shown in Appendices 1.2 and 1.3 (Ganguli, 1995; Ray, 1997). Certainly, this means that more materials will enter into the system, requiring more work-force and units for their recycling. Otherwise, the propensity for cross-contamination and its effects on the quality of recycled products will be increased to a greater extent from the current levels, and thus will continue to cause substantial problems in their processability down the chain of successive recyclings.

The reason behind the possibility of unsustainable circumstances developing in the future plastics recycling is the poorly maintained waste disposal system currently utilised in Dhaka, Calcutta and Delhi (Haque et al, 1997; Haque, 1997, Rashid, et al, 1995; Ahsan, et al, 1992b; Giri and De, 1992). In these cities, there is also an almost total lack of concern and legislation on environmental and hygiene issues related to waste disposal and recycling. For instance, a significant portion of domestic waste is thrown indiscriminately on the streets by both the slum dwellers, who may not have space for in-house storing of refuse, and also the relatively well off. While this is partly owing to the absence of a developed system of house to house collection, lack of civic consciousness is also an important factor. As a result, discarded plastics in individual and communal heaps along the road side get contaminated with (i) refuse from domestic, commercial and institutional establishments, (ii) silt from drain cleanings, (iii) human faecal matter released by the slum dwellers to open drains and the road, and (iv) animal manure coming from the large number of freely roaming cattle and dogs. In these cities, although hospital plastic waste should be treated separately for sanitary reasons, these are also disposed of with other hospital and municipal wastes and subsequently collected manually for recycling (Giri and De, 1992; Haque, 1994; Kumar, 96)

The content of plastic in municipal solid wastes (MSW) in India varies between 4-5 per cent, compared to 1-2 percent in the cities of Bangladesh (Table 1.2), while the amount of plastic waste found in the municipal dump yard of Calcutta was 1.07 % in 1995, up from 0.65% in 1992 (EIP, 1996; Ganguli, 1995). These statistics clearly indicate that the role of

recycling is extremely significant. Similar to the case of Bangladesh, 60 to 80 per cent of recyclable plastics in the MSW streams of Indian cities and towns gets collected by the waste pickers for recycling (Ratra, 1994; Ganguli, 1995).

Table 1.2: Municipal solid waste by materials in some cities of developing and developed countries (In % by weight).

Type of Waste	Dhaka[1] 1994	Dhaka[2] 1990	Calcutta[3] 1994	Sao Paulo[4] (Brazil) 1991	UK Cities[5] 1995	Western Europe[6] 1995	USA Cities[7] 1992
Organic Waste	87.5	84.7	43.2	61.0	20.2	34.0	26.0
Paper and cardboard	6.9	8.3	8.3	14.0	33.2	27.0	41.0
Glass	2.1	1.5	26.7	2.0	9.3	9.0	8.0
Plastic	***1.8***	***2.0***	***5.3 (India: 4-5)***	***13.0***	***11.2***	***8.0***	***7.0***
Metal	1.2	3.4	1.5	3.0	7.3	5.0	9.0
Miscellaneous	0.5	0.1	15.0	5.0	17.8	17.0	9.0

Data Sources: 1/ Haque and Bell, 1998; 2/ Nahar, 1990; 3/ Ratra, 1994, Kundu, 1994 and Ganguli, 1995; 4/ Wells, 1994; 5/ Waite, 1995; 6/ APME, 1997; 7/ PRF and CPRR, 1992.

Since there is no large scale mechanised recovery and recycling of solid waste in any of the cities of Bangladesh and India, the manual recovery by individual scavengers at the city dust bins as well as the dumping sites is carried out on an massive scale. However, despite the physical conditions of recyclables mixed with other MSW, the waste pickers and recyclers carry out their strenuous jobs very effectively in an efficient way, under extremely difficult conditions (Haque et al, 1997). Dirty cross-contaminated and mixed plastics collected from the mixed waste streams have to be passed through a number of recycling stages before they can be converted into feedstocks. It would appear probable that the greater the number of stages required for collection, transportation, sorting, cleaning and processing the recyclables, the higher the cost of recycling overall. In order to reduce this cost, recyclables are not treated properly and thus remain contaminated. Consequently, quality deterioration in the recycled products is inherent to the current recycling system, but this needs to be determined objectively by an in-depth study.

1.3 Status of Plastic Waste in the Developed Economy

In the economically developed countries, campaigns are organised by the Government departments, municipalities and plastics industry for plastic waste collection and separation schemes, by offering incentives and subsidies. A comprehensive survey performed by the Association of Plastics Manufacturers in Europe (APME) reported that, in 1995, seventeen countries in Western Europe (WE) produced altogether 2794.7 millions tonnes of 'total waste' of which 16.3 million tonnes (0.6 %) was 'post-user plastic waste'. Out of this amount of 'post-user plastic waste', only 7.6 % had been mechanically recycled within the region and another 2.4 % was exported outside WE for mechanical recycling, and 16.8 % (up from 14.7% in 1990) was thermally recovered by combustion for energy recovery - a fate widely considered to be unacceptable (APME, 1997; PWMI, 1990). Less than 1% was also recovered by 'feedstock recycling' (APME, 1997). The rest (around 72 %) had been landfilled because this portion of the 'post-user plastic waste' is too dirty, too small or too flimsy to be handled.

In 1995, Germany was at the top of the Western European countries by recycling 15.3 % of its 1.8 M tonnes of household plastic waste of which 9.7 % was by mechanical recycling and 5.6 % was by feedstock recycling (APME, 1997).

According to the APME's survey report, although the UK relies less on household plastic waste incineration with (5 %) or without (8 %) energy recovery than almost all other Western European countries, mechanical recycling rates of this waste are even lower (APME, 1997). In 1995, this country alone generated a total of 2.2 million tonnes of 'post-user plastic waste' which includes 1.3 million tonnes of 'household plastic waste'. In the same year, 4.6 % of the 'post-user plastic waste' and 0.6 % of the 'household plastic waste' were mechanically recycled. This relatively higher success in recycling 'post-user plastic waste' is directly attributed to the supply of large and clean LLDPE, LDPE and HDPE waste mainly from the agriculture and commercial sectors which accounted for 65 % of the total amount in 1995. A total of 13,208 tonnes of post-user plastic waste was imported and mechanically recycled, and no 'feedstock recycling' was recorded in that year. Along with Greece and Portugal where 100 % landfilling of household plastic waste is operated, the UK is also in highest position among the WE countries by landfilling 86.4 % of plastic waste (APME, 1997).

These facts imply that very little pragmatic attempt has been made in the previous years to further the progress of post-user plastic waste, and even less for household plastic waste, recycling efficiency in the developed world, although there is a general belief that the environment must be benefitted by promoting re-using and recycling of discarded materials which might otherwise destined to landfill site (Cooper, 1994). In recent years, the momentum for recycling has been enhanced in most of the European Community (EC) countries by their Governments' challenging target of recycling for all post-user recyclables with a great concern over plastic waste (DoE, 1995; Bontoux and Papameletiou, 1996). Nevertheles, there are admonitory predictions drawn by Cooper (1994) that since consumers or end-users are not directly responsible individually for their waste disposal, waste management problems will not be tackled anyway. He added that development of waste recycling under this circumstances will prove to be "an obstacle rather than a stepping stone if it diverts attention from the more crucial changes that are now demanded to reduce the excessive throughput of energy and materials in the economy (of the industrialised countries)" (Cooper, 1994).

There are many reasons behind the difficulties inherent in plastic recycling in industrialised countries. From the economic point of view, energy is consumed as the waste products are collected, processed and reprocessed, and subsequently, when recycled products are distributed. Additional amounts of energy are consumed in the movement of plastic waste materials between the different stages of recycling because plants involved are often long distances apart. Other shortfalls include the limited market for recycled plastics and stringent legislation on their applications on the grounds of health and safety (DoE, 1991; WET, 1993, Waite, 1995). With regard to the difficulties attached to technical aspects, the molecular characteristics and control over processing conditions are of paramount importance in quality control, and the problems of uncertainty in these two issues would be exacerbated by the more variable input of a recycled polymer (Bassett, 1993). The possible resulting uncertainty in the properties of recycled polymer may render the already existing difficulties in polymer identification and separation more problematic in the multi-sectoral recycling system where different types of discarded virgin and/or recycled plastic products arising from different sources are subsequently reprocessed.

1.4 Research Hypothesis

The hypotheses to be tested are that:

- There may be a stage in the foreseeable future of 'post-user plastics waste' recycling, dependent on the rate and nature of quality deterioration over the course of successive recyclings, the average duration between successive recyclings, and the levels of contamination in the feedstocks, after which recycled plastics will become increasingly worthless in terms of their market value for production of consumer products.
- This deleterious level of deterioration in quality of recycled products will come at an earlier point and have much greater economic significance for Dhaka, Calcutta and Delhi closed-loop plastic recycling systems compared to the UK open-loop recycling system, since the former deals with a much higher percentage of contaminated plastic waste being recycled and its overall importance in the production of recycled plastic products is substantially greater.

1.5 Aims and Objectives

The aim of this study is:

> to determine the future scenarios of plastic recycling in terms of deterioration in the quality of the plastics which have undergone successive recyclings, taking into account socio-economic, technical, and legislative factors as these vary with the levels of economic development.

The project has four related objectives:

- to determine the effects of successive reprocessings on the properties of virgin and general scrap plastics (HDPE);
- to develop mathematical models for the future scenarios of plastic recycling in terms of these effects of reprocessings, taking into account all possible limitations of recycling at different levels of economic development;
- to use the Bangladesh, India and the UK case studies to test and validate the future scenarios derived; and finally,
- to outline alternative routes of disposal of plastics and suggest areas of future research towards ways of achieving better plastic waste management systems for both the developing and developed economy.

1.6 Scope of the Study

The scope of the study is confined to mechanical recycling of post-consumer plastic waste, but other disposal options of plastics are reviewed to identify other appropriate alternative(s) where mechanical recycling is not viable, and also, to suggest areas for future research. The project is based on case studies on Bangladesh, India, and the UK, with data from other developing and developed countries referred to for comparison and addition. To examine the effect of successive recycling on the quality of recycled plastic, post-consumer High Density Polyethylene (HDPE) is chosen due to the *simplicity* of its polymeric characteristics (Walker, 1995). HDPE waste materials, which had already been recycled different numbers of times, were collected from the Dhaka, Calcutta and Delhi waste streams. Bangladesh has been given 60 per cent of the scope of this research, with an equal share of 20 per cent each for the other two case study countries - India and the UK.

1.7 Working Definitions

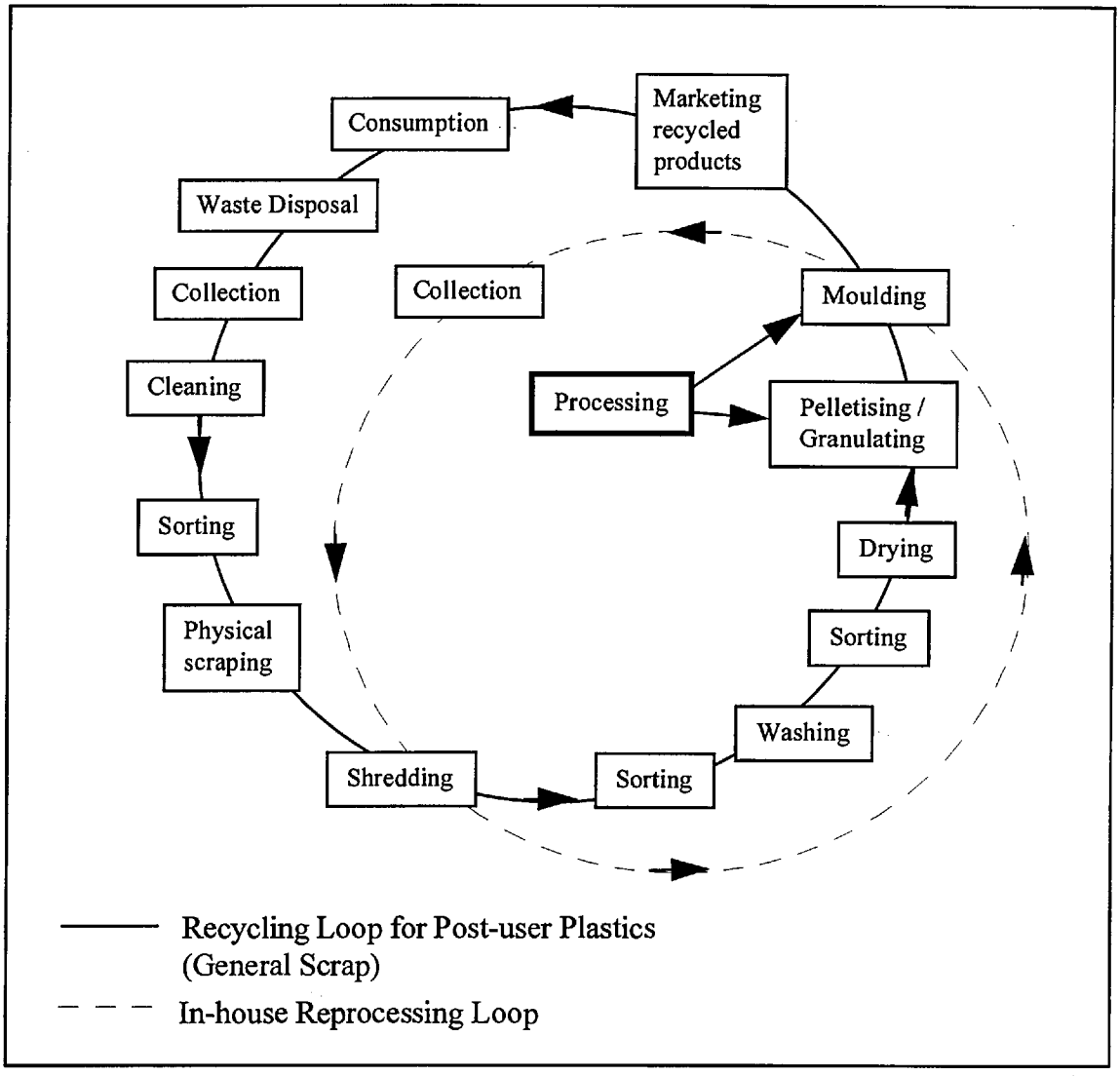
For the purposes of this study, the following definitions have been set up. The term *'processing'* is used to refer only to those steps in mechanical recycling of plastic which involve melting and reforming of the waste, and thus, it includes either pelletising, granulating, agglomerating or moulding and excludes sorting, shredding, washing and drying (Figure 1.2). The term *'reprocessing'* refers to the in-house activities (moulding-collection-shredding-moulding) performed repeatedly in this study for sample plastic feedstocks, in order to distinguish it from *'recycling'* which includes all steps involved in a closed-loop cycle of genuine post-user plastic wastes (Figure 1.2). In this study, *'post-user plastic wastes'* are often referred to *'general scraps'* discarded from all different sources after their useful service life in use and/or re-use.

1.8 Approach to the Study

The project started with a literature research of the background history of plastic waste recycling in both the developing and developed world, to make a detailed analysis of the present status, impediments/limits, prospects and uncertainties in mechanical recycling of the waste (Chapter 2). Attempts were also undertaken to identifying alternative

recycling techniques, and other disposal options, taking into account technical, economic and social limitations of recycling at different levels of economic development (Chapter 2).

Figure 1.2: Working definitions of processing, reprocessing and recycling in a closed-loop recycling system for the purpose of this study.



Parallel with the literature research, a number of contacts were made, as both written communication and telephone conversation, with the experts interested in plastic recycling. These attempts were made with the view to obtaining information about the overall performance of plastic waste recycling industries in the UK. Several meetings were conducted successfully with some appropriate persons to obtain some crucial guidance and

suggestions to design and develop the research methodology and thus develop the project in a sound manner. Very positive responses and fruitful results were received from the experts contacted and met, who expressed interest in the potential prospects of the project.

On the basis of the outcome of the literature review and contacting persons, the scope of the study was demarcated. After reaching this point of the study, a short questionnaire (Appendix 1.4) was developed and sent off through mailing to a total of 110 British plastics recycling companies selected from the list in 'the Directory of UK Companies Involved in the Recycling of Plastics' (BPF, 1993) and 'Waste, Recycling & Environmental Directory 1994' (DPA, 1994).

Following the experts' opinion, an attempt was made, between November 1995 and April 1996, to perform field investigations to observe techniques and performance of plastics recycling in Dhaka (Bangladesh) and also, in Calcutta and Delhi (India). Along with gathering all available necessary information, a number of representative samples of virgin and general scrap HDPE plastics were collected from the waste streams of Dhaka, Calcutta and Delhi (Chapter 3). Parts of these samples were moulded successively into 2 litre jerry-cans using a single screw extrusion-blow-moulding machine in Dhaka, and sample specimens were collected. These specimens, along with certain amount of the virgin and scrap materials used in Dhaka, were brought London for laboratory experiments in May 1996. All general information collected from Bangladesh and India is tabulated and discussed in Chapter 3. In this chapter, the procedures used in the sample feedstocks collection and moulding them into jerry-cans are also elaborated.

All the sample specimens brought from Dhaka were tested at the School of Polymer Technology, University of North London, London, to determine the effects of in-house successive reprocessings on their mechanical and rheological properties (Chapter 5). After that, the virgin HDPE plastics brought from Dhaka which had been reprocessed successively under known processing conditions, and sample specimens were collected and tested at the same laboratory premises. All these experimental data relating to virgin plastic are discussed in Chapter 4. Other data collected through field investigation and laboratory tests of the general scrap plastics are presented in Chapter 5. In Chapter 6, combining both the fieldwork findings and laboratory test results, future scenarios of plastics recycling in a closed-loop system of Bangladesh are determined through

developing some mathematical models using FORTRAN 77 computer programming language. Implications of these future scenario models have also been discussed in this chapter. The results from the questionnaire survey on the UK plastics recycling companies are analysed and elaborated, in conjunction with the findings obtained from literature research, in Chapter 7.

The hypotheses set out above have been tested. On the outcome of the predictions arising from this hypothesis testing, conclusions for the study and recommendations for alternative routes of disposal of plastics are outlined in Chapter 8, with a view to suggesting areas of future research for selecting appropriate disposal options feasible for different levels of economic development.

CHAPTER 2:

Socio-economic , Technical and Legislative Factors Governing Plastics Recycling

2.1 Introduction

Global *plastic waste* production is about 85 million tonnes per year and it is expected to be 100 million tonnes by the year 2000 (Raghupathy, 1994). Out of this huge amount of discarded plastics, different countries generate and recycle them at different rates, depending on their social, economic, technical and legislative characteristics. In this respect, a literature research had been carried out to explore how these factors act upon the individual country's level of achievement in plastics recycling. On the basis of the results obtained from the literature research, a brief discussion with examples has been made in the following sections of this chapter, in order to highlight some pertinent issues.

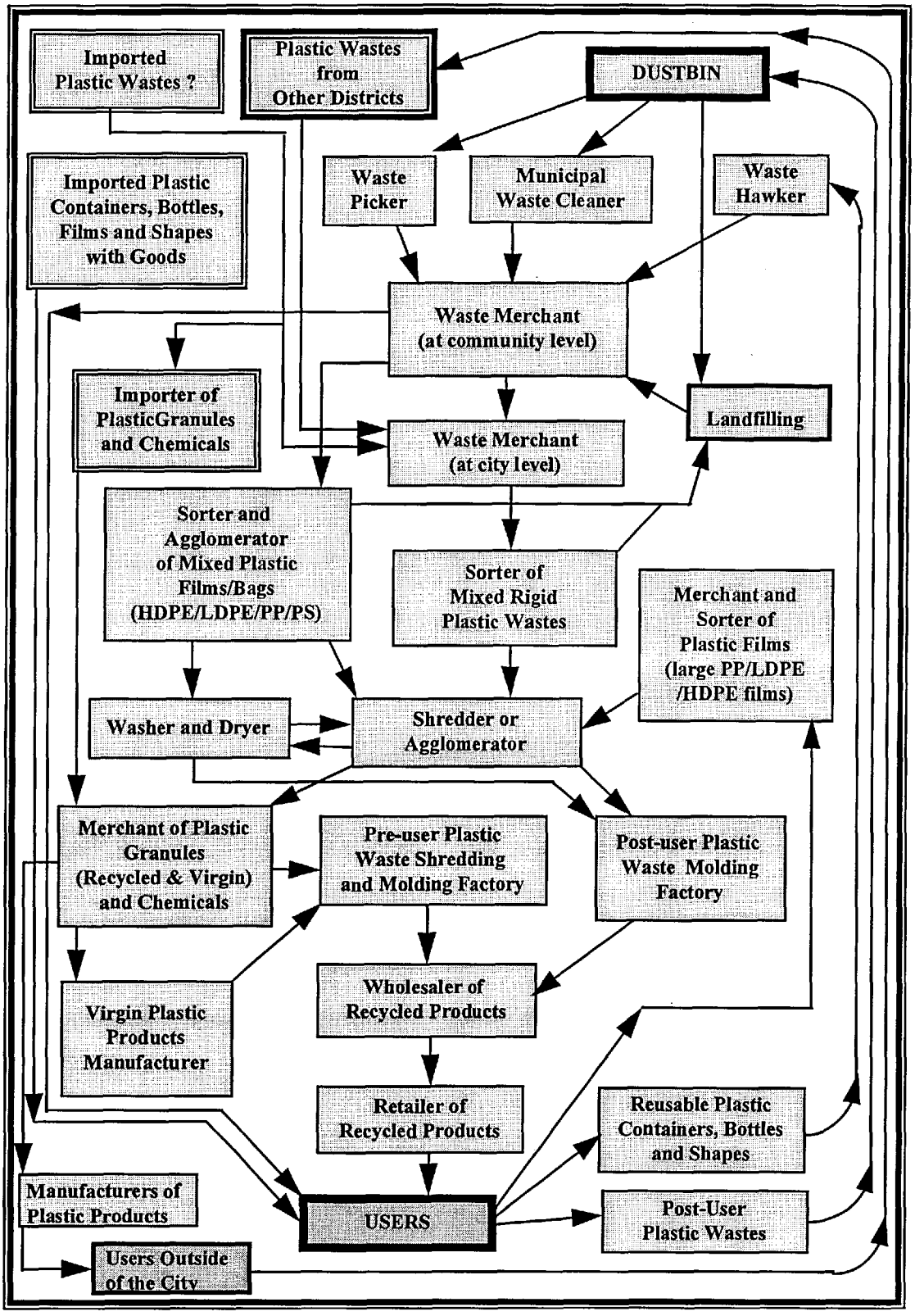
However, little *basic research* has been carried out and published on plastics recycling in developed countries, whilst in developing countries this is effectively zero. In particular, very few experimental studies relating to the effects of successive recyclings on the quality of plastic products have been performed and published. In addition, in most cases test specimens employed have been made of carefully prepared plastic feedstocks rather than general post-user plastic waste, thereby introducing an unrealistic element into the studies.

2.2 Plastics Recycling in the Developing Economy

2.2.1 Factors Favouring Plastics Recycling in Bangladesh

Waste disposal system and quality of recycled products: Imported virgin pellets is the main original source of plastics in Bangladesh (Haque and Bell, 1998). A variety of new products are produced out of these pellets and marketed, mostly within the country. After their useful service life (including use and reuse), scrap plastics are disposed of in the mixed waste streams of the country, and hence, they become dirty, cross-contaminated and mixed with other wastes. Haque et al. (1997) reported that various types of plastic waste were identified in the solid waste stream of Dhaka city. They added that these wastes arose from a diverse range of sources within the city and also from premises in other cities and rural areas of the country (Figure 2.1). Once the materials have accumulated at some point, these are eventually brought to the old parts of the capital city for processing.

Figure 2.1: Sources and routes of plastics waste streams in Dhaka city.



Source: Haque et al., 1997 and Haque, 1994.

These post-user scrap plastics collected from such waste streams have to be passed through five to eight recycling stages of the current plastic recycling system up to converting them into feedstocks for producing recycled articles (Haque, 1997; Haque 1994). All these activities, shown in Figure 2.1, are performed repeatedly over the course of each cycle of successive recyclings.

However, the dirty and mixed characteristics of post-user plastics (Photograph 2.1a) have hindered optimisation of recycling efforts and increased the number of intermediate stages (Photograph 2.1b) between the source of arising and the moulding factory. Similarly, the number of units operating at different stages of recycling also vary in accordance with the volume of work at each particular stage (Haque, 1994). It is also likely that the quality of the recycled plastic products depends on the external physical conditions and mechanico-chemical characteristics of the plastics reclaimed from the waste streams. In most cases, a general picture of deterioration in the physical appearance of the recycled plastic products is easily identifiable.

The operator of a manually operated plastic moulding machine (Photographs 2.2a and 2.2b) has no control over barrel temperature, ram pressure, dwell-time or other variables, but using reclaimed material, this crude moulding process produces items of marketable quality (Photographs 2.1), as reported by Haque (1994) and Vogler (1985). They added that this moulding machine could produce a superb finished product using reclaimed materials as shown in Photographs 2.1c and 2.2c. This finishing quality level was quite the equal of that expected from far more sophisticated machinery (Vogler, 1985). Credit for this high finishing quality is due to another vigorous and skilful hand operated industry in Islambagh, Dhaka, which manufactures the dies with carefully smoothed and chromium plated moulding surfaces for plastics moulders (Photograph 2.2a).

Forces driving the recycling system: Along with the gradual advancement in this informal sector of plastics recycling over the last few decades, the system is being driven by the dynamics of the socio-economic forces involved. There are the following economic and social forces, which have concentrated all stages of recycling in the old part of Dhaka city as shown in Figure 2.2:

◊ minimisation of the transport costs of the materials from the location of one stage to another by permitting use of manual methods,



Photograph 2.1a:

Different types of plastics accumulated for hand sorting, Dhaka.



Photograph 2.1b:

Manual sorting of plastics from mixed waste stream - an intermediate stage of plastics recycling, Dhaka.



Photograph 2.1c: High quality finished recycled plastic containers.

Photograph 2.2:
(a) Moulding operator opens up die and is about to push down melted tube;
(b) The operator pushes down melted tube and is ready to close the die for air blow;
(c) Jerry-cans moulded out of virgin (right) and recovered (left) HDPE.

(a)



(b)

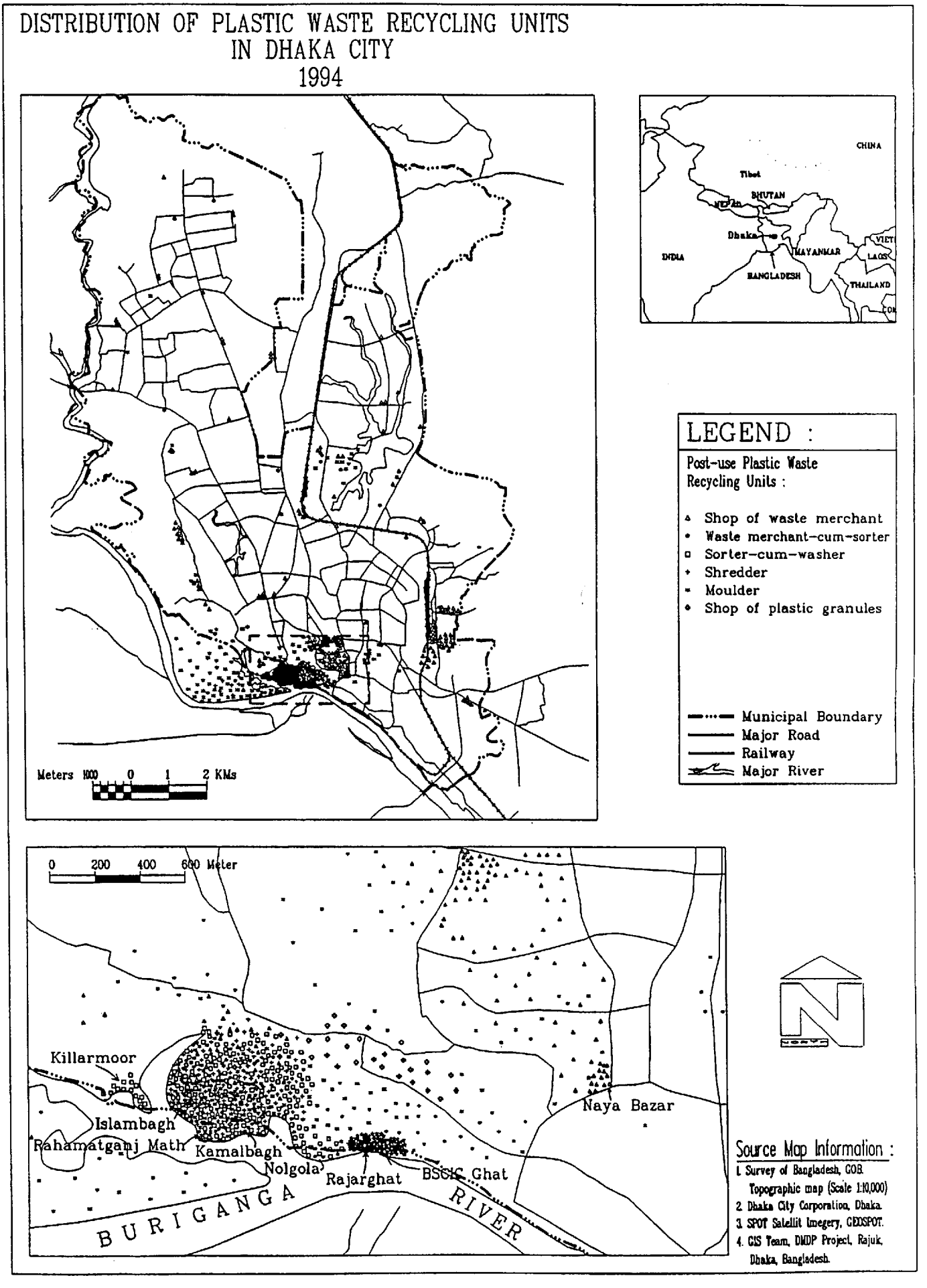


(c)



Source: Fieldwork, 1996.

Figure 2.2:



Source: Haque, 1994.

- ◊ gain of economic benefit to the recycling units through providing services from the complementary factories located in the same place and involved in producing and repairing recycling equipment,
- ◊ utilisation of quay facilities of the nearby *Buriganga* river for loading recycled products and unloading recyclables,
- ◊ gain of business facilities from the nearby wholesale markets of recyclate and recycled products, and
- ◊ utilisation of the benefit of availability of skilled recycling workers from the inhabitants of this area.

In particular, in *Islambagh*, which can be designated as a 'plastic community', like the 'plastic village' around Hanoi city, Vietnam (Simpson, 1994), the majority of its inhabitants make their living from trading, processing and moulding plastic waste (Figure 2.2). This small area can also be characterised as a central place of plastic waste processing for the whole country, with a result that movement of material between the different stages of recycling occurs over short distances. Haque and Bell (1998) reported on the basis of the data obtained from a field survey in 1994 that out of more than 600 plastic products manufacturing factories in Bangladesh, using both virgin and/or scrap plastics as raw materials, about 500 were located in and around Dhaka city. They also mentioned that even within Dhaka city, more than 60 per cent of plastics recycling factories were concentrated in *Islambagh* and its periphery. Therefore, the nature of flow of the plastics recycling system in the country is single directional and towards Islambagh. Recyclable plastics are transported into Islambagh and after passing through a number of processing and manufacturing stages, recycled products are delivered to almost all corners of the country and abroad, when and where required.

Overall, in the case of Bangladesh, recyclability and utility of plastic waste and higher costs involved in importing virgin plastics on the one hand, and economic necessity of the waste pickers and recycling workers on the other hand, act as the 'push forces' to recycle successively the waste. Moreover, at the same time, the large demand for relatively low cost recycled plastic products from the increasingly growing urban and rural population of the countries across the south-south-east Asian region acts as a further stimulus for future sustainability of the recycling in Bangladesh and India.

It has been estimated that a total of 12,133 tonnes of post-user plastic waste is generated and recycled per year in Bangladesh, which was 38 % of the annual imports of virgin thermoplastics in 1993 (Haque and Bell, 1998; Haque, 1994). The major portion of the rest presumably currently remains in use, having a long life. Only about 2-5 %, consisting of those fractions which were small or difficult to collect, were destined to end up in landfill sites and low lying ditches (Photographs 2.3 and 2.4).

Since the beginning of the 1990s, recycled plastic products of relatively good quality in the form of bags, sacks, floor coverings, wall or ceiling coverings, toys, etc. have been exported from Bangladesh to Nepal, Bhutan, Pakistan, Myanmar, Saudi Arabia, Hong Kong, Vietnam, Australia, Russia, USA, France, Germany and UK as shown in Appendix 2.1 (BB, 1996a). Pasi (1996) and Singh (1996) reported that India has also exported a substantial amount of recycled plastic products. In order to meet the national and international demand of low cost recycled plastic products, both India and Bangladesh import plastic waste intermittently for recycling. During 1990-93, a total of 16 tonnes and 11,951 tonnes of plastic waste were imported by Bangladesh and India, respectively, from Australia, Canada, Germany, UK and USA (Greenpeace, 1994).

Current difficulties: Haque and Bell (1998) have identified the following major difficulties which are currently facing by the plastics recycling system in Dhaka:: (a) contamination of discarded plastics with clay, dust, metal and organic materials, and in particular, cross contamination of hospital plastic waste with pathogenic substances; (b) lack of sufficient and continuous supply of water to wash plastics properly and also, of power supply to run recycling machinery regularly; (c) existence of old, manual, inefficient, and unhygienic washing techniques; (d) impurities remaining in the washed plastics causing problems in reprocessing and raising cost of reprocessing as a number of extrusions through filters are required to screen out impurities; (e) deterioration in the quality of the recycled articles, due to repeated reprocessing and successive inevitable addition of impurities into recycled plastic, which affects the physical characteristics such as appearance and ductile-brittleness, chemical structure and composition, and processability.

Photograph 2.3: A cross-sectional view of an abandoned landfill site, Dhaka



Photograph 2.4: Un-recovered film plastics, mainly shopping bags, in a ditch, Dhaka.



They have also mentioned that, in some cases, the complete separation of dissimilar plastics is neither economically feasible nor technically possible in the context of Dhaka city. When the quantity of any particular resin type in a waste lot is not sufficient to recycle separately, the sorter keeps it in the mixed plastic category. In addition, the plastic fractions, which have degraded environmentally and/or lost in the physical strength due to repeated processing, are also classified as mixed plastics. Thus co-mingled plastics recycling may be the only option at present for this mixed plastics. Therefore, the end products of different coloured and mixed plastic waste are very low grade deep coloured, mainly black, recycled products (e.g. containers for tobacco preparation, betel leaf mixture, herbal medicine) due to the heterogeneous structure of the resulting mix. In this study, the effects of manual control over the degree and method of processing and reprocessing that took place during plastics recycling by semi-mechanised or man-powered machines, is often reflected in the quality of the recycled products.

2.2.2 Factors Favouring Plastics Recycling in India

Current plastics recycling infrastructure: Although the Indian history of plastic recycling goes back to the 1920s, the large scale introduction of plastics to the country was in the late 1960s when a simultaneous approach for recycling these was also adopted (Ratra, 1994). In the initial stages a cottage industry used to produce bangle using scrap cellulose acetate film and acrylic scrap (Raghupathy and Kala, 1994; Ratra, 1994). The recycling technology following the traditional method - grinder, mixture and extruder - as practised in India, has now matured over the years. It has been noticed by Ratra (1994) that, for a long time, no attempts were made to qualify and quantify the plastic wastes that were being recycled and the products made out of these recycled materials. Nor have there been any attempts to regulate or standardise the quality of recycled materials used and to identify the application of these in terms of both - consumer and products. He also reported, the production and consumption of plastics were 424,000 tonnes and 966,000 tonnes, respectively, in 1991 (Ratra, 1994). This is expected to increase at the rate of 30 per cent per year with the availability of around 2.5m tonnes of various plastic materials with plans for expansion and diversification of the petrochemical industry by the close of this century. He added that out of the recycled plastic materials, which were mainly converted into consumer items (Photograph 2.5), PVC accounted for share of 45 %, LDPE

for 25 %, HDPE for 20 % and polypropylene 7.6 % and other polymers including polystyrene for 2.4 %.

Photograph 2.5: Recycled plastic containers market at *Raja Katra*, Calcutta.

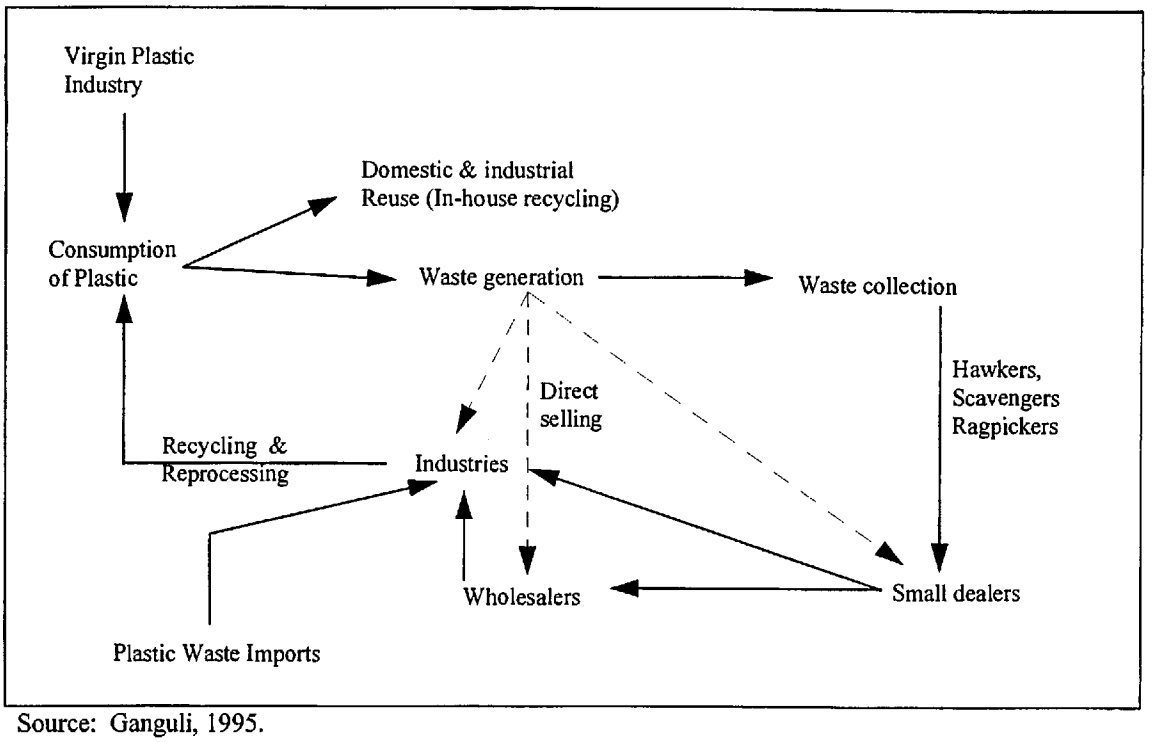


Raghupathy and Kala (1994) noted that the per capita consumption of plastic in India was estimated to be less than 1 kg, but was expected to be about 3 kg by 2000, which is much less than the present use of 89 kg per capita in USA and about 15 kg globally. According to his opinion, no finite value can be given at this stage for the growth in usage of plastics as introduction of plastics in everyday life and the commercial usage does not follow any definite pattern in India.

Opportunities and impediments in plastic recycling: The plastic waste recycling system in India has its own merits and demerits. Problems relating to driving this system are low in India (as in Bangladesh) compared to Western countries due to specific socio-economic compulsions and socio-cultural ethos. The average consumer in both the developing countries, particularly the housewife, provides a natural support to an eco-friendly product management system by retaining empty containers for storing food/non food products for very long periods. India has also a highly efficient plastic waste collection and recycling system through manual labour (Parasuraman and Banerji, 1994),

which is very much similar to the system operating in Dhaka as shown in Figure 2.1. The system is basically propelled by economic forces and sustained by very low cost manual labour for collection and sorting. In addition to these, the imported waste plastics from industrialised countries are also cheap, enabling and encouraging the small manufacturers in the country to buy such raw materials for reprocessing by involving the entire family (Figure 2.3).

Figure 2.3: Life cycle of plastics in the city of Calcutta and Delhi.



Source: Ganguli, 1995.

Overall, similar to the case of Bangladesh, recyclability of plastic waste, large demand for recycled products and higher costs involved in importing or producing virgin plastics on the one hand, and economic necessity of the waste pickers and recycling workers on the other hand, act as the 'push forces' to recycle successively the waste. Raghupathy and Kala (1994) believed, *"there (in India) may be more than one stage recycling in which case the quality of plastic has been seen to be deteriorated after every stage of recycling"*. Ratra (1994) also said, *"the recycling of plastics is carried out sometimes four times i.e. four grades of recycled material are available, each time characteristics of particular recycled material change."*

Moreover, following the traditions of reuse, repair and recycling, plastics recycling systems in the cities of Dhaka, Calcutta and Delhi are always characterised by the following socio-economic and environmental conditions:

- ◊ Use of low cost locally made recycling equipment used for granulating, washing, blending, extruding, pelletising and moulding, although none of these has either temperature control devices or emission trapping attachments;
- ◊ The availability of a highly skilled and experienced work force for the labour intensive work of plastics recycling, in particular for the difficult task of sorting the wastes according to their polymer types, and for manufacturing, repairing and maintaining recycling equipment;
- ◊ Availability of the relatively cheaper women workers employed in sorting, cleaning and separating material within small, poorly lighted and ventilated rooms where they are exposed to all sorts of smoke and dust;
- ◊ Unrestricted scavenging and collection of recoverable materials by the waste pickers and storage of unsegregated dirty wastes in road side waste shops within residential, commercial and other areas;
- ◊ Open disposal of unused or charred material arising from recycling, into the environment by burning or dumping;
- ◊ Unawareness about escaping of dust, respirable and total particulates, and probably some toxic, carcinogenic and teratogenic substances from these recycling activities and open burning of mixed plastic films. Thus working under a filthy conditions is also generally accepted by the recyclers;
- ◊ Lack of workers' motivation rather than ignorance about hygienic conditions of the work places, where most of the operations of sorting, cleaning, separation, etc. are carried out, may lead to several health problems of the workers at all different stages (Haque et al., 1997). Hygienic issues involved can be categorised either in terms of work force exposure to toxic substances or contamination of the recycled end products.

Trade in hospital plastic wastes: Bharati Chaturvedi and Ravi Agarwal (of *Srishti* - an environmental group based in Delhi) reported that infected medical plastic wastes e.g. disposable syringes, surgical gloves, blood bags and intravenous tubes were disposed of with bloody dressings and used needles (Kumar, 1996). The most serious danger comes from these waste items to the waste pickers and recyclers during pillaging them from the

poorly guarded waste stores and their reprocessing stages. Disposable syringes were collected for reuse as well as for recycling the plastic. According to their report, this sort of pilfering and recycling for sale took place in every hospital, even those where these were incinerated. In this respect, last year, the Indian government drafted legislation that made it compulsory for all large hospitals to build incinerators to manage their waste, and smaller ones would be required to send their waste to outside incinerators (Kumar, 1996). However, Srishti's investigators found this objective difficult to achieve because none of the existing incinerators operates at a high enough temperature, and all are potential sources of highly toxic emissions including dioxins, furans and heavy metals. Despite this, the authorities seem to see incinerators as the only way to solve the problem of their hospital waste. Regarding this issue of hospital plastic waste recycling, nothing is different in Dhaka and Calcutta from those operating in Delhi's thriving black market in hospital waste (Haque, 1994; Ganguli, 1994). However, detailed investigation on these issues is not within the scope of the present study.

Government initiatives for plastics recycling and pollution control: According to the view of Raghupathy and Kala (1994), Indian plastics recycling units are running under the small domestic sectors without having adequate pollution control measures and any of the prescribed standards, neither for recycled products nor for the environment at work place. However, a number of regulations were proposed for plastic waste as early as in 1990 when a Waste Management Council was constituted (Raghupathy and Kala, 1994). The Council undertook the task for assessing the problems related to all non-hazardous wastes that require special schemes for reuse and recycling. *'Plastics were considered to be one of the important constituents of the wastes to be recycled and not permitted for going into the environment'*, Raghupathy and Kala (1994) reported. In 1992, the National Conservation Strategy and Policy Statement on Environment and Development and the Policy Statement for Abatement of Pollution were brought out by the Ministry of Environment and Forests. In those documents, the generation of wastes and their improper management were identified as major causes for environmental imbalances in India. The problems had been identified and action programmes were being prepared for different areas.

2.3 Plastics Recycling in the Developed Economy

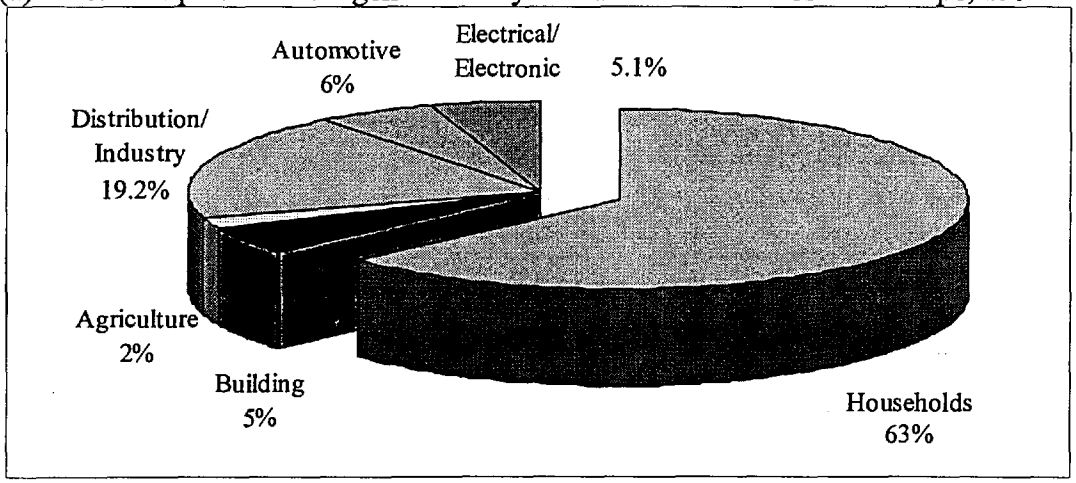
In the industrially developed countries, virgin plastic is cheap to produce compared with recycling discarded plastics to meet the demand for this material. Therefore, plastic wastes have been regarded as disposable, low specification materials and hence they are going into landfilling. In the case of the UK, sanitary landfill of wastes have been followed since 1916 (Staudinger, 1970), and it is still the least costly and the most widely practised method for disposal of different types of plastic waste (APME, 1995). For instance, a recent survey carried out by the Association of Plastics Manufacturers in Europe (APME) reported that Western Europe generated 16.1 M tonnes post-user plastic waste in 1995, of which a major proportion (63 %) was attributed to household sector (Figure 2.4a). In that year household plastic waste also accounted for 8 % of the total household waste (Figure 2.4b), and more than two thirds (68 %) of this household plastic waste was landfilled (Figure 2.4c). As a result, current questions are as to what best usage can modern society make out of the waste instead of landfilling them, and, what would be the most practical option to deal with the problems involved, so that at least some benefit, social or material, can be derived from its disposal.

First of all plastic manufacturing industries have started thinking about the above approach and have begun to reclaim and recycle a small proportion of their production wastes that they had traditionally been discarding, following the advances in polymer technology and economic pressure brought about by rapidly increasing new material prices preceded by the oil price shocks in the 1970s (Buckley, 1995).

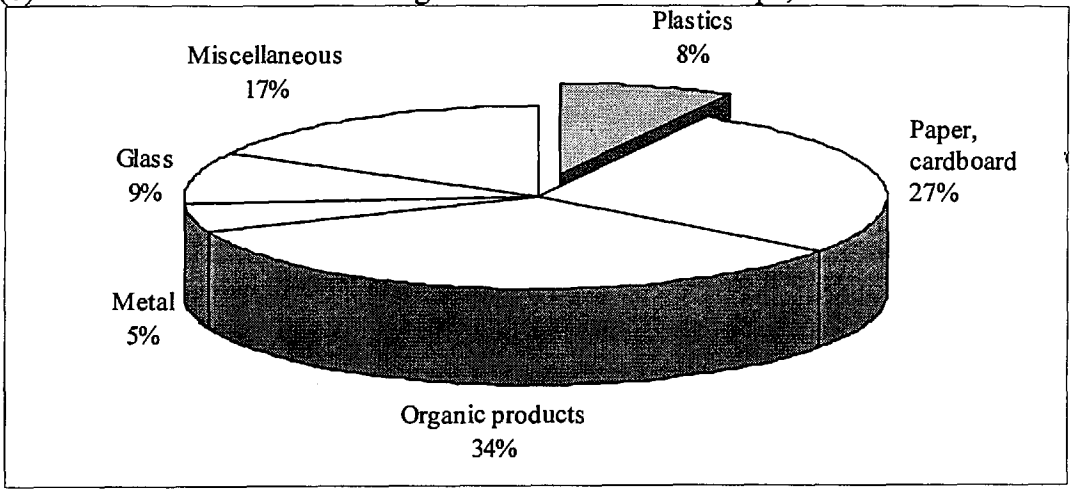
In recent years, advances in the technology and sophistication have significantly improved the quality and performance of plastic and have opened out a wide range of its applications. As a consequence, nowadays a considerably large amount of plastics is being consumed by the developed countries, resulting in accumulation of different types of plastic wastes which forms a very visible component of the general waste management problem. They are generally perceived as being harmful to the environment. As a result there is a strong consumer and political pressure to reduce, reuse and recycle plastics rather than dispose of them by conventional techniques - landfill and incineration without energy recovery. Therefore, a range of applications of waste plastics have been reviewed under the following three potential routes of disposal listed below:

Figure 2.4: Post-user plastic waste generation and management in Western Europe (WE), 1995.

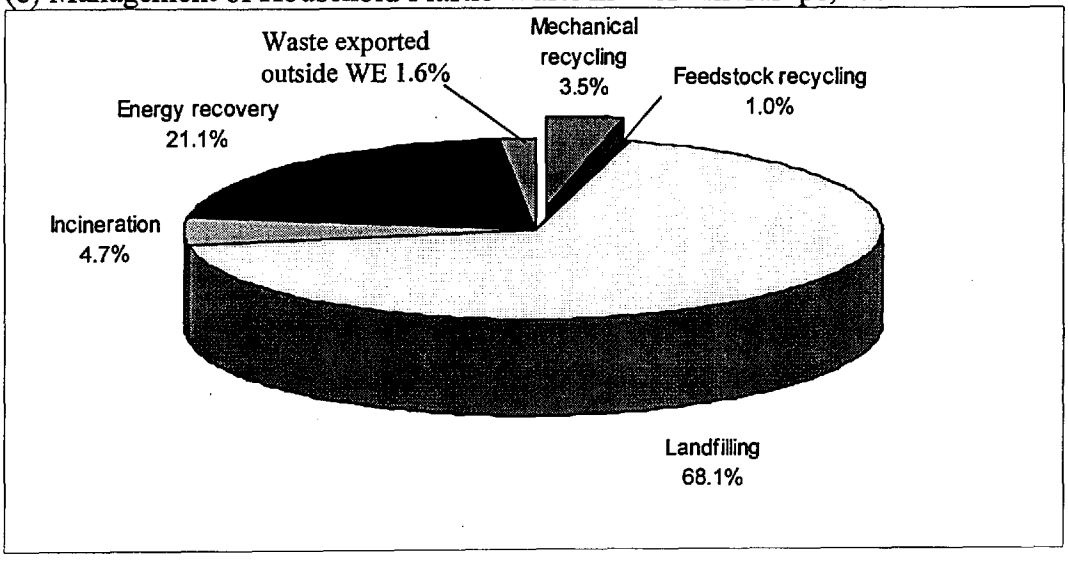
(a) Post-user plastic waste generation by end-use sector in Western Europe, 1995.



(b) Plastic in household wastes generated in Western Europe, 1995.



(c) Management of Household Plastic Waste in Western Europe, 1995.



Data Source: APME, 1997.

- **Mechanical or material recycling :** melt down plastic to make new products,
- **Energy recovery other than by incineration:** burn or heat up mixed plastic waste to recover its energy content or to use it as a reducing agent, and
- **Chemical or feedstocks recycling :** take the waste to a stage further and reduce it to petro-chemical feedstocks - the raw material for plastic making.

Notwithstanding these possibilities most plastic currently ends up being incinerated or buried in landfill because recycling is fundamentally uneconomic. Research has therefore been directed both towards enhancing natural degradative processes and also towards innovative recycling methods. Although the current focus is on material recycling, in an integrated waste management situation, all three options will have to be considered. It is clear that fundamental scientific research is required in these areas, in order to develop an environmentally friendly and economically sustainable alternative method of recycling. In this vein, many pilot projects are being run in the leading Western European countries, such as the UK, Germany and France, including USA and Japan, and these are described in the following sections, along with their potential opportunities, current barriers and future challenges.

2.3.1 Mechanical Recycling: Economic and Technical Factors

2.3.1.1 Plastic wastes in Western Europe

In 1989, Western Europe produced 11.4 M tonnes of post-user plastic waste, of which only 0.8 M tonnes were mechanically recycled, another 1.7 M tonnes thermally recovered and the rest disposed of with no recycling as shown in Table 2.1 (Bontoux and Papameletiou, 96). Yet in 1991, when this region generated 14.6 M tonnes of post-user plastic waste, just 1.1 M tonnes were recycled (Table 2.1). By 1994, waste had risen by one fifth to 17.5 M tonnes, but recycling was still running at 1.1 M tonnes (Luesby, 96). However, the results obtained by a recent overview survey on European plastic waste carried out by APME (1995) indicated that there has been a drop in post-user plastic waste generation in Western Europe in 1995 (Table 2.1). This drop is 8 % from the total in 1994, which may be an artefact of the relatively higher precision in estimating the values involved in the survey. Apart from some progress in incineration to energy recovery (16.8 %) and recent introduction of feedstock recycling (0.6 %), post-user plastic waste

Table 2.1: Management of post-user plastic waste by end-use sectors in Western Europe (WE), 1989-1995. (Unit: x 10^6 tonnes/year).

Waste Management Options		**1989**[a] Total amount	**1991**[b] Total amount	**1994**[b] Total amount	**1995**[c] Total amount	% of the total	Agriculture (%)	Building (%)	House-holds (%)	Distribution / Industry (%)	Automotive (%)	Electrical/ Electronic (%)
No Recycling	Landfill	8.9	–	–	11.4	70.7%	70%	96%	68%	66%	79%	85%
	Incineration		–	–	0.5	3.2%	0%	0%	5%	1%	0%	0%
Thermal/Energy recovery		1.7	–	–	2.7	16.8%	3%	0%	21%	11%	14%	13%
Mechanical Recycling	Recycling locally*	0.8 (7.4%)	1.1 (7.5%)	1.1 (6.3%)	1.2	7.6%	27%	4%	3%	22%	7%	2%
	Export**	–	–	–	0.2	1.0%	0%	0%	2%	0%	0%	0%
Feedstock Recycling		–	–	–	0.1	0.6%	0%	0%	1%	0%	0%	0%
Total		**11.4**	**14.6**	**17.5**	**16.1**	100%	100%	100%	100%	100%	100%	100%

Notes: *Included intra European trade to be recycled; **Outside Western Europe to be recycled; "–" Data not available.
WE - Austria, Belgium, Luxembourg, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Swede, United Kingdom, Norway, and Switzerland (APME, 1997).
Data Sources: [a]Bontoux and Papameletiou, 1996; [b] Luesby, 1996; [c]APME, 1997.

management efficiency through mechanical recycling remained almost the same in 1995 (7.6 %) as it was 7.4 % in 1989 (Table 2.1). The highest mechanical rate (27 %) was in the agricultural post-user plastic waste which was followed by the distribution / industry sectors (22 %). This waste from the households sector is the least suitable with a rate of 3%, followed by the electrical and electronic sector which accounted for 2%.

Following this trend the UK, chemical consultancy, Tecnon, forecast that the recycled plastics market will have claimed just 3 per cent of the UK plastics market by 2000 (Luesby, 1996). Therefore, the consultant added that, since the quality of recycled plastic is often generally perceived as lower than original plastic, the former needs to be at least 30 per cent cheaper than virgin material to compete. Moreover, as the European Commission (EC) Packaging and Packaging Waste Directive requires the industry to recycle 15 per cent of plastic waste (DoE, 1995), APME estimates that mechanical recycling will only be able to contribute half of this (Lascelles, 1994). In order to meet the Directive's requirements, other means, notably feedstock recycling, will have to be developed. Currently, feedstock recycling is operated commercially only in Germany among the Western European countries.

2.3.1.2 Mechanical recycling in Germany, UK, France and Italy

The proportion of plastics contents in municipal solid waste (MSW) in Germany is 7.8 per cent which was the second highest in Western European countries, preceded by France with 8.0 per cent (Table 2.2). By 1995, this content of plastic in MSW increased in most of the Western European countries including the UK, except Germany where a substantial decrease occurred as shown in Table 2.2. This decrease is directly related to Germany's prevailing waste recovery activities under the auspices of its legislatively controlled waste management system (Helberg, 1995). Having nearly the same population size, plastic in MSW in France was 10 % compared to 9 % and 8 % in its other European counterparts - UK and Italy, respectively.

In 1995, Germany produced 3.1 M tonnes of post-user plastic waste, up from 2.6 M tonnes in 1989 (Table 2.3). A similar rise in the amount of this waste category also occurred in France, Italy and UK. Over the years, the households sector has always dominated other end-use sectors in generating plastic waste, as is shown in Table 2.3.

Table 2.2: Total plastic contents in municipal solid waste (MSW) by Country / Region.

Country / Region	Population, 1995[a] (x 1000)	Plastics contents in MSW	
		1989[b]	1995[a]
Germany	81,337	7.8 %	6 %
United Kingdom	58,295	7.0 %	9 %
France	58,109	8.0 %	10 %
Italy	58,261	7.0 %	8 %
Western Europe (WE)	384,204	7.3 %	8 %

Data Source: [a] APME, 1997; [b] PWMI, 1990.

Table 2.3: Post-user plastic waste generated locally by end-use sector and by country, 1989 and 1995. (Units: ktonnes /year)

Country	Total 1989[a]	Total 1995[b]	% of the total by country, 1995[b]						
			House -holds	Distri- bution	Auto- motive	E & E	Bldg.	Large Industry	Agricul -ture
Germany	2,636	3,181	57 %	18 %	6 %	6 %	7 %	5 %	2 %
France	1,800	2,997	68 %	11 %	6 %	4 %	5 %	4 %	2 %
Italy	1,601	2,450	67 %	13 %	5 %	5 %	4 %	4 %	3 %
UK	1,830	2,193	59 %	16 %	7 %	6 %	6 %	5 %	2 %

Data Source: [a]PWMI, 1990; [b]APME, 1997. Note: E & E = Electrical and Electronic; Bldg. = Building.

In Germany, the tough national packaging laws have pushed the plastic waste management process furthest in Europe, along with tremendous innovations and progress in feedstock recycling and energy recovery of post-user plastic waste (Table 2.4). A detailed discussion on feedstock recycling as a technical factor follows. About 11 % of local post-user plastic waste was recycled mechanically in Germany in 1995, preceded by Austria (15.3%) and Switzerland (11.9 %). Particularly in the case of mechanical and feedstock recycling of local household plastic waste, Germany is in the first place with a combined recycling rate of 15.3 %, followed by the second highest rate of 7.0 % in Austria (APME, 1997). Germany is also in a higher position in incineration with energy recovery of post-user plastic waste (Table 2.4).

However, the major counterparts of Germany such as UK, France and Italy are operating at much lower levels in all aspects of their post-user plastic waste management as presented in the Table 2.4. On the other hand, in 1995, these latter three countries landfilled and incinerated their post-user plastic wastes without energy recovery at considerably higher rates ranging from 71-86 % and 3-4 % compared to 50 % and 2.3 % for landfilling and incineration, respectively, in Germany.

Table 2.4: Post-user plastic waste management by country and management method, 1995.

Waste Management Options		Germany	France	Italy	UK
Post-user plastic waste (ktonnes / year)		3,181	2,997	2,450	2,193
No Recycling	Landfill[1]	49.9 %	70.8 %	77.7 %	86.1 %
	Incineration[1]	2.3 %	3.2 %	3.5 %	3.9 %
Incineration with energy recovery		25.2 %	20.1 %	10.1 %	4.0 %
Mechanical Recycling	Local	10.9 %	4.2 %	5.5 %	4.6 %
	Import[2]	0.1 %	0.5 %	2.1 %	0.6 %
	Export[3]	8.5 %	1.3 %	1.1 %	0.5 %
Feedstock recycling[4]		3.1 %	0.0 %	0.0 %	0.0 %

Notes: [1] Percentages are calculated on the basis of their Western European (WE) averages.
[2] Intra European import; [3] Outside Western Europe to be recycled.
[4] In WE, only Germany operates this method of recycling.
Data Sources: APME, 1997.

Cost of plastic recycling in Germany: Plastics recycling cost was about US$ 1950 (DM 3000 or £1250) per tonne, which was the twice the cost of virgin plastic in 1994 (Lascelles, 1994; Brandrup, 1995). Mr. Johannes Brabdrup of VKE (a German plastics trade group) believe that if they have to pay such a high fee for plastics recycling, then the competitiveness of this product is in real danger (Lascelles, 1994). This is due to the fact that the market for recycled plastic remains smaller than the amount of available material collected from the waste streams. For example, Germany which pioneered plastics recycling in Europe is collecting wastes through its 'Duales System Deutschland (DSD)' - a government-backed and industry funded system for recycling consumer plastic packaging (Brandrup, 1995) , but lack of a national market for collected plastic waste causes rising stockpiles (DoE, 1995; Luesby, 1996). Therefore, there are moves to export some of DSD's plastic waste to some neighbouring countries and Asia (Ratcliffe, 1994; Luesby, 1996; Greenpeace, 1994). Meanwhile, the French and Belgian national schemes 'Eco-Emballages' and 'Fost Plus', respectively, have also been hampered by the amount of material built up in Germany (Luesby, 1996).

Germany's joint venture with Belgium - HDPE bottle recycling: Currently, Germany is the only country with a formalised collection process, but even this process does not ensure that Germany's total bottle market (representing about 85,000 tonnes of HDPE per year) is finding its way to the recycler (Ratcliffe, 1994). Bales of crushed HDPE bottle

collected and separated in Germany are transported by truck across the border to Ravago Plastics Luxembourg SA (RPL) in Virton, Luxembourg, Belgium. The company, with a capacity of 300-500 tonnes of post-consumer recyclate per month, is a joint venture of RPL of Belgium, Dow Europe SA of Netherlands and OTTO Waste management Ltd. of Germany to recycle HDPE bottles. The feedstock is made up of HDPE bottles collected from several countries, but most of the raw material comes free from Germany via OTTO and the DSD as subsidised by the DSD system. Each year the Virton plant is inspected by a German quasi-governmental organisation (TUV) to decide whether to grant a certificate of approval enabling the Virton facility to continue to receive and recycle DSD materials for a further twelve months.

Ratcliffe (1994) noted that, in September 1992, RPL's first equipment trials achieved 80 per cent efficiency, proving the basic concept of the technology to be correct. Nonetheless, there remains the problems of the continuing level of contaminants, despite the care that is taken to maintain the purity of feedstock. The processing line can remove most dirt, but PET is the component close to HDPE in composition which can cause a problem. This has led to a line made up of three consecutive separation steps, in a combination of washing and friction which removes the contamination caused by labels, aluminium and other unwanted materials. However, contamination of finished recyclate has been virtually eliminated, but another challenge still remains. Aluminium as a contaminant can appear in tiny pieces, usually with a plastic film coating, because metalised plastic labelling is a recent development in the packaging industry. The recycler will soon be addressing this problem via electrostatic separation technology.

2.3.1.3 A close look at the UK's plastic waste

By 1970, the share of plastics in the domestic and trade refuse was between 1% and 2% by weight (Staudinger, 1970). After 25 years, in 1995, plastics contributed 9 % to the total municipal solid waste, up from 7 % in 1989 as shown in Table 2.2 (APME, 1997; PWMI, 1990). APME (1997) reported that the UK generated a total of 2.2 M tonnes of post-user plastic waste, of which 59 % is attributed to household sector alone and 2% is accounted for by the agriculture sector as the lowest contribution (Table 2.3). However, according to a thorough green vetting by the Organisation for Economic Co-operation and

Development (OECD), Britain's performance in recycling is among the lowest in OECD Europe and its recycling targets fall far short of the Government's targets (Lean, 1994). Plastics recycling in the UK is still in its infancy, with the main work being the production of granulate feedstock for the manufacturing of new items.

A survey of plastics recyclers in the UK indicated that, between June 1990 and June 1991, 185,000 tonnes of plastic were recycled (Ogilvie, 1992). Out of this recycled plastic, 52,000 tonnes was estimated to be post-user plastics and was mainly film plastics which are usually less contaminated, for example, single grade LDPE pallet-wrap discarded by supermarkets. So far as 'domestic plastic packaging waste' is concerned, however, the plastic industry remained recycling's poor relation until 1995, as it had yet to achieve a 1 per cent recycling rate (APME, 1997; ENDS Report 245, 1995). In fact, the tonnage had gone down, from 3,150 tonnes in 1993 to 2,900 tonnes in 1994. Here it is assumed that part of the reason for the apparent reduction in recycling activity in 1994 is more careful analysis of the amounts collected.

Table 2.5: Amount of Plastic Waste Recovery, Demand and Supply in the UK (In tonne).

Year	Domestic Plastic Packaging Waste (According to *Recoup* prediction)[a]				Domestic Plastic Waste (According to *PRG* plan)[b]
	Already recycled[b]	Projected recovery	Estimated demand	Supply shortfall	Projected recovery
1993	3,150	--	--	--	--
1994	2,900	4,100	5,250	1,150	5,000
1995	--	5,800	9,000	3,200	9,000
1996	--	7,600	12,000	4,400	--
1997	--	10,000	--	--	--
In future*	--	14,000	--	--	--

Note: *Provided enhanced funding. '--' = Data not available. PRG = Producer Responsibility Group.
Source: [a] ENDS Report 238, 1994. [b] ENDS Report 245, 1995.

Plastics recycling organisation -Recycling of Used Plastic (Containers) Ltd. (RECOUP) has calculated figures for UK recovery, demand and supply of PET, HDPE and PVC bottles as shown in Table 2.5. The figures show that demand for recycled plastics has been rising steeply and markets for recovered plastic bottles are far outstripping supply from collection schemes. Accordingly, collection mechanisms would need to expand rapidly if new markets come on stream, otherwise recycling could be restricted unnecessarily. RECOUP is calling for financial support from the packaging chain's Producer Responsibility Group (PRG) to help to raise collection levels. It was estimated that given

current funding arrangements and markets, some 10,000 tonnes of plastic will have been collected in 1997, up from 3,150 tonnes in 1993; and this could increase to 14,400 tonnes given enhanced funding (ENDS Reports 238, 1994).

A number of publications have reported environmental, technical, economic and social barriers to plastics recycling in the UK (Cooper, 1994; DoE, 1991; Ogilvie, 1992; Roy, 1991; Sarson, 1992; Waite, 1995; Williams, 1991). Problems lies in the raw material. More than two-thirds of plastic waste ends up in the municipal solid waste stream, as one-part plastic to 11 parts of everything else by weight (Luesby, 1996). As a result, the difficulty of collecting, cleaning, sorting and processing plastic waste adds vastly to the costs, and thus, recyclers face extraordinary burdens in gathering and preparing their raw material. All these issues are elaborated in Chapter 7 by relating them to the UK's plastic recycling scenarios. Since the literature surveyed has mentioned very little about the effects of successive reprocessing on the properties of post-user general scrap plastics, Chapters 4, 5 and 6 of this study have attempted to cover these aspects so far possible within the time and resource limitations of the present work.

2.3.1.4 Success and shortfalls of new sorting techniques: technical factors

Plastics coding system in the USA: A partial success has been achieved by the efforts of a Society of Plastic Industries coding system in the USA (US-SPI System), which moulds plastic products with numbers from one to seven into plastic containers for seven major plastic types. A field survey by Recycle Worlds Consulting in Winconsin showed that even where plastics were sorted by code, unwanted plastics and non-plastic accounted for nearly 20 per cent of the material collected. This amount of unwanted material could turn a profit of US$ 500 (£320.50) a day at a plant recycling pure plastics into losses of between US$ 100 and US$ 700 a day, the group estimates (Luesby, 1996). It was also mentioned that even one PVC bottle can render an entire batch of recycled PET unusable. To reduce this problem it is required to mark the material type on all plastics in an obvious location. Unfortunately, this is not always done: marked parts may have their material codes hidden in awkward places, usually for cosmetic reasons; older plastic parts are not marked, or the marking is inadequate.

Automated sorting by Infra-red Spectroscopy: In future, automated sorting systems based on FT-IR (Fourier Transform Medium Infra-Red spectroscopy) technology may help with plastic identification and sorting. For the larger plastic waste items, machinery is coming on to the market that can classify plastics by measuring their interaction with light. In this respect, two mobile plastic identification devices ('Polyana' and 'Tribopen') have been developed by the Ford Motor Company Ltd. with the assistance of the University of Southampton, UK (Intex, Undated). These are now marketed under the brand name of Intex Technology Ltd. throughout Europe and USA. Similarly, Bruker in Germany has also launched a spectroscope that can classify industrial plastic waste in just four seconds. However, application of any of these automated sorting techniques is not practicable for most of the plastic that find its way into municipal wastes and becomes dirty. Worse still is in the case of multi-layered plastic containers. Typical is a cheese wrapper, which might contain 14 layers of different plastics, with one designed to keep air out, another provided for strength, and so on.

Solution for mixed plastics under mechanical recycling: One solution for unsortable plastics has been the development of uses for recycled mixed plastics. As a non-biodegradable alternative to wood, it has found a small market. A recent example is that Scamia, a leading French plastics processor, has developed stakes for mussel farmers, as part of a project to find uses for recycled mixed plastics, reported by Luesby (1996). Commercial production of the stake is to be launched by the group soon. These are 25 per cent more expensive than the wooden equivalent, but they are also more than 50 per cent lighter, more flexible, can be used all year round, and last longer (Luesby, 1996). Similarly, a Norwegian producer has launched a moulded carrier bag for large drink bottles, made from industrial plastic waste, while other plastic recyclers are marketing crates, pallets, seed trays, park benches and even pig pens. However, it is vital to any recycling operation to find out an end-use application prior to the setting up of the plant. If there is no application or consumer ready to take the recycled material, the loop soon becomes congested and must eventually stop.

2.3.1.5 Effects of successive recycling and contaminants on the polymer properties

Thermoplastics allow repeated melting and moulding, but there can be some deterioration of mechanical properties and chemical structure of polymer because of the high temperature moulding process which reduces the polymer chain length (DoE, 1991; Ogilvie, 1992). Since these shortened polymers cannot be removed, it is reported by DoE (1991) that various additives e.g. impact modifiers can be used to improve their mechanical properties. However, in the case of successive recycling, Sorrie (1995) mentioned on the basis of his industrial experience with BP Chemical, UK, that effect of successive recyclings on the chemical properties of recycled polymer is fairly minimal, but some effects/changes on their processing characteristics and mechanical impact failure are observed during the product manufacturing stage. This problematic issue has become more certain in Williams's (1991) opinion that deterioration in properties is inevitable for plastics when these are processed successively, and thus degraded recyclates ultimately affect both the manufacturing process and quality of recycled plastic products.

In this respect, some of the previously published papers, back to the early 1980s, report on experimental work related to the effect of repeated processing and of additives on the properties of injection-moulded polypropylene co-polymer (Williams and Bevis, 1980a, 1980b, 1981 & 1982). Some of the important and very relevant findings, for example, are:

> *"The use of up to 100% of recycled polypropylene compound as feedstock material does not lead to a decrease in impact properties of injection-mouldings, (rather) tends to cause an improvement in impact performance.....*, (but) *.....The use of 100% of material which had been recycled two or more times prior to the final conversion process lead*(s) *to a substantial decrease in impact strength.* (Moreover,) .... *Successive recycling results in a marked change in molecular weight, moulding skin thickness and impact properties and would not normally be considered appropriate in commercial practice* (Williams and Bevis, 1980b).

It has also been noted by Williams & Bevis (1980a) that a significant difference in the reproducibility of shot weight and in the dimensions of finished products can result from the variation occurring from the use of irregularly shaped recycled flakes. They added that although regularly shaped particles can be obtained from extruding and pelletising processes, these processes cause further molecular degradation of the polymer involved (Williams & Bevis, 1980a).

Regarding the effects of extraneous particles (contaminants) in feedstock, Sorrie (1995) has expressed a similar view as to the effects of successive processings. He has pointed out that contaminants do not affect significantly the chemical properties but they affect mechanical properties of recycled plastics. According to Sorrie's practical experience, 'strain at break' and 'impact strength' of recycled PE are reduced by 30% and 30-60% of that of virgin PE, respectively. According to his view, these result from the presence of particulate contaminants such as PP and paper fibre in the feedstock used. For instance, 10% PP contaminants in PE feedstock can reduce impact strength performance of recycled PE by 50-60% of that of virgin material (Sorrie, 1995). Scheirs and Camino (1996) also reported that the deleterious effects of contamination on recycling polymers can result from the presence of other polymers, from the packaging contents, by the environment, and/or by degradation of the polymer.

These findings partially reflect the reality of the problem of quality deterioration in recycled polymer, because the compounds used as feedstock in their experimental works were carefully prepared to avoid the inclusion of impurities, and with no allowance given for any adverse effect of contamination on the products' quality which is one of the vital problems of current recycling of post-consumer plastics. Bassett (1993) believes that the class of post-user plastics are less easily identifiable, and adequate characterisation of sorted material prior to reprocessing cannot be achieved satisfactorily because these are generally small, dirty and cross-contaminated, and hence difficult to identify and not easily sortable. He adds that this leads to the increased risk of deterioration in the quality of the plastics when recycled and this risk must rule out the viability of their large-scale recycling in the foreseeable future.

As polymers degrade due to the effects of many different factors involved, therefore there are, in any case, limits to the number of times which plastic can be recycled (Roy, 1991; Cooper, 1994). Thus all these uncertainties in the resultant quality of recycled plastics give the impetus to consider the quality deterioration problem as an important and timely subject to be examined in this research project.

2.3.2 Energy Recovery: Technical and Economic Factors

2.3.2.1 Use of mixed plastic agglomerates in the steel industry

Germany's steel making industry has come up with a novel solution to the problem of waste plastics. They grind the waste into particles and use them as reducing agent and also as the partial source of energy in the steelmaking process. A German company - Stahlwerke Bremen, which pioneered the use of waste plastics in the blast furnace, has replaced 30 per cent of the heavy oil it uses with a corresponding amount of plastic agglomerates (Greenfield, 1996). The aim of replacing heavy oil and coal with plastics in blast furnaces is not to get the maximum energy out of them but to use their ability as reducing agents. They can be just as effective as oil or coal. Plastics make ideal agents for removing oxygen from iron ore in blast furnaces and save on oil and coal as well. It takes 100 Kg of heavy oil to produce one tonne of pig iron (pure iron) which is used to make steel. At temperatures of more than 2,000 ^{0}C, plastics split into mainly carbon monoxide and hydrogen. These combine with the oxygen in iron ore to form carbon dioxide and steam as well as the pig iron, which collects at the bottom of the furnace. The main modification to the blast furnace is to the injection system which instead of spraying oil into the furnace must combine oil and 5 mm pieces of plastic. Injection tubes obviously have to be bigger. The preparation of the material is also different. Waste plastics are cut up and granulated by frictional heat into pieces not much bigger than 5 or 6 mm.

Overall Efficiency: Germany's use of the process relies on the DSD. This system claims that the overall efficiency of using plastics in the blast furnace as a reducing agent and as an additional energy source, is around 80 per cent. Some 30 per cent of the plastic's latent energy content is used thermally (Greenfield, 1996). It has also been noted that incinerating plastics to produce electricity has an overall efficiency of just 40 per cent, but there have been fears that poisonous dioxins and furans could result from the chemical reaction inside the furnace if plastics which contain chlorine, such as PVC, are used. These were quelled when independent studies found that concentrations of these agents were well within legal limits, although a limit of no more than 2 per cent chlorine content by mass has been established (Greenfield, 1996).

Supply of waste: The Bremen steelworks receives a subsidy of US$ 135.7 (DM 200 or £87) per tonne of plastics it uses as part of a three-year contract with the DSD. The steelmaker has invested US$ 10.2 M in the project to convert from oil injection. With the money it gets for the 70,000 tonnes of plastics it uses every year and the amount it saves on oil, the pay back period will be less than a year (Greenfield, 1996).

Greenfield (1996) has reported that German industry will soon have the capacity to recover all waste plastics that are collected through DSD and use of these plastics in the blast furnace process will play a key part. Planned regulations on waste from cars and electronics will mean more potential supplies for steel industry.

Marketing the technology: With the attractive subsidies from the DSD, the technique is finding wider use in the country and many national industries are lining up to use this technique. The Bremen steelworks is looking to patent the injection system as there are many companies interested. Companies from Austria, Sweden and Japan have already approached the steelworks. The UK plastics industry is also looking to the German experience as one answer to its growing problem of automotive plastic waste. The UK car industry generates between 300,000 to 400,000 tonnes of waste plastics every year. Although recycling initiatives have been set up by the automotive industry, few manufacturers recycle their plastic waste due to the high cost of collecting, transporting and sorting plastic parts (Greenfield, 1996). The British Plastics Federation is in negotiations with the car industry and says that reports from the DSD are very positive and show that waste plastic could be a valuable part of pig iron manufacture. If British Steel, which already recycles automotive steel, extends its interests to take back automotive plastic waste as well, transport costs could probably be reduced.

2.3.2.2 Producing gas by cracking plastics and other waste materials

Scientists at Waste Gas Technology in Romsey, UK, came up with a technique, called Thermocrack, for producing a gas from municipal rubbish. The waste was heated at up to 1000 ^{0}C, which cracks the waste materials into smaller gas molecules. The researchers estimated that the heating potential of the gas produced from the Thermocrack process was between 70 and 100 per cent of that of natural gas, which means it could be

used in gas turbines and other high-efficiency power generation plants (Guardian, 1995). The process works on anything from rubber, plastics and tyres to sewage sludge. Once the gas produced is cleaned, it can be converted directly into heat or used for power generation.

As well as plans to use Thermocrack in the UK, there is also interest from Africa, the Far East and Pacific Rim countries. Kevin Whiting of Waste Gas Technology says that this process could be extremely important, particularly in the developing nations where they have two problems - waste disposal plus a shortage of power, which could be solved simultaneously (Guardian, 1995).

2.3.3 Feedstock/Chemical Recycling: Technical and Economic Factors

Feedstocks recycling, in other words, breaking the material down into basic chemicals is still in the experimental stage. A range of feedstocks recycling techniques have been developed by different developed countries (Winter, 1993; Layman, 1993; Menges, 1995; Ogilvie, 1996):

- Depolymerisation or thermal decomposition
  - ⇒ Chemolysis
  - ⇒ Hydrogenation
  - ⇒ Pyrolysis
- Chemically induced breakdown (degradation)
  - ⇒ Oxidation
  - ⇒ Hydrolysis
  - ⇒ Chemolysis.

All these processes unzip the constituent molecules down (depolymerisation) into fairly large molecules that form fluids or gases, which can be easily separated in this form from impurities and alien molecules (Menges, 1995). The purified materials can than be used as basic raw materials in refineries or petrochemical and chemical production in place of natural gas or oil.

2.3.3.1 Recycling of Mixed Plastic Waste: Polymer Cracking

Layman (1993) said that depolymerising single condensation polymers - urethanes, polyethylene terephthalate (PET), nylon, and polymethyl methacrylates, for example - through chemolysis processes is relatively straightforward. However, the big challenge is still there, which is associated with mixed plastics wastes that can be broken down only by cracking back to basic oil feedstocks.

The technology currently being used for depolymerised the waste to chemical feedstocks is variously called feedstock or chemical recycling, polymer cracking, or tertiary recycling. There are many industry efforts under way to cope with the messy job of dealing with post-user plastics, using feedstock recycling technology. In this line of research and effort, some important industry efforts are described in the below.

a) The Conrad advanced recycling project in the USA: 1995

Pearson et al. (1995) reported that the USA generates 240.79 M tonnes of municipal and industrial waste each year, of which 4 to 11% by weight is accounted for plastic. They added that nearly 80% of the total waste is being landfilled. In order to provide a long-term solution for mixed plastic waste, the Conrad Industries, Inc. (Chehalis, Washington) jointly with the American Plastics Council (APC) have successfully developed an auger kiln reactor that applies heat to dirty and unsorted plastic resins and additives collected from post-user waste stream to produce high quality liquid petroleum products, e.g. crude oil, naphtha or gas oil (Meszaros, 1995). This process produces such end products which have wide market applicability as those are equivalent of the products made from virgin materials in terms of their quality. This advance recycling process does also not require grinding, shredding and extruding processes which are currently used in conventional plastics recycling. However, there are some technical and economic hurdles which will be met by the further studies currently undertaking at the Conrad's bench, pilot, and commercial scale units.

Pearson et al. (1995) also reported a pilot project on a novel waste gasification system developed by the Energy and Environmental Research Corporation (EER) in the areas of advance plastics recycling in the USA. This project is funded by the US-EPA, the Gas

Research Institute and the Southern California Gas Company. This system is based on a 'spouted bed' reactor which gasifies high heat content heterogeneous plastics (may be contaminated with toxic organic compounds and heavy metals) to produce environmentally safe fine particles (Pearson et al., 1995).

b) Polymer cracking by a European Consortium in the UK: 1993 to 1998

British Petroleum (BP) chemicals has been working on a new recycling project since 1989 (Layman, 1993). A European consortium of five leading petrochemical companies has sponsored a feedstock recycling plant located next to BP's refinery at Grangemouth near Edinburgh, UK. They are BP, DSM of the Netherlands, Elf Atochem of France, Enichem of Italy and Fina of Belgium(O'Neill, 1997). The plant is an experiment to address one of the most difficult issues facing their business - plastic recycling - in order to promote an alternative.. It could have important repercussions for the petrochemical industry. Their US$ 6.2 M (£4 M) pilot project was launched in 1993 aiming to convert mixed plastics into gas, followed by distillation into wax and oil, which was due to complete by 1994 (Lascelles, 1994). However, their project of 750 tonnes a year has now been successfully completed, and they are going to take decision in 1998 to built a large plant and to commercialise the technology (O'Neill, 1997). The new plant will be able to use about 25 ktonnes of mixed plastic waste to feed into its polymer cracker, and end products will be supplied to a existing Naphtha crackers to produce monomers for the polymer industry.

c) Germany's feedstock recycling techniques: VEBA, BASF & ESPAG - 1993

In Germany, the pressure to recycle mixed plastics has been increasing, which was spurred by a 1991 federal packaging ordinance that mandates recycling a large portion of packaging materials. DSD is pushing for recycling plastics to make feedstock to augment mechanical recycling capacity. Both VEBA and BASF have substantial plants capable of recycling 55, 000 tonnes of mixed plastics per year (Lascelles, 1994). According to DSD, the recycling of used plastic packaging into raw materials is particularly effective as far as energy balance is concerned (Layman, 1993). Germany is currently leader in feedstock recycling technology (APME, 1997). Different necessary researches on various aspects of this area of advanced plastics recycling have been performed in the country: methods of processing feedstocks (Menges and Lackner, 1995; Brophy and Hardman, 1995); petrochemical processes for recycling plastics (Kaminsky and Sinn, 1995; Niemann, 1995;

Gebauer and Stannard, 1995); reduction in blast furnaces (Niemoller, 1995); depolymerisation of polymethyl methacrylate (Brand, 1995); solvolytical processes for special plastics (Klein, 1995; Kopietz and Seeliger, 1995; Reuschel, 1995; Bauer, 1995).

Hydrogenation of plastics into syncrude by VEBA: VEBA's technology has adopted its coal liquefaction technology located at Bottrop, Germany. This technology involves a hydrogenation process in which plastics' chemical compounds are broken up to produce a syncrude (synthetic oil) for the petrochemical industry. In 1992, the company began running test on liquefaction of mixed plastic waste. It successfully ran 59 tonnes of liquefied mixed plastic, combined with refinery residues, turning out a syncrude that was fed into VEBA's refinery at Gelsenkirchen, Germany (Layman, 1993).

Since April 1994, the Bottrop plant has been using the above technology, and it hydrogenates 40,000 tonnes per year of synthetic waste collected by the DSD (Lindemann, 1995). The synthetic wastes ranges from plastic bags and yoghurt cartons to computer casings. In the process, the wastes are mixed with heavier oil residues before adding water. Cost of converting these is about US$ 524 (DM 800 or £336) per tonne, reported by Lindemann (1995). This cost is considerably more than the expense of burning it. He reported that managers at the Bottrop plant believe that they can reduce costs to around US$ 306 (DM 450) if they can increase the capacity.

Feedstock recycling by BASF: In September 1993, BASF, one of Germany's biggest chemicals makers, decided to built a pilot plant to recycle mixed plastics into feedstocks. Now it has built a similar plant to that of VEBA at its headquarters in Ludwigshafen, Germany. The company has so far spent US$ 18.5 million (DM 40 million) to build the plant that converts 15,000 tonnes of plastics a year (Lindemann, 1995). Instead of adding water, it heats the waste to create a mixture of liquids and gases which are then distilled to produce a variety of raw materials such as butane, which can be used to manufacture other chemical products. One kilogram of waste yields 900g of reusable raw material. BASF has also offered to build a plant that can handle 300,000 tonnes of waste - if it receives a subsidy of up to US$ 238 (DM 350) per tonne from the DSD (Lindemann, 1995).

Gasification of plastics by ESPAG: Another successful technology was announced by DSD in July 1993 (Layman, 1993). The technology is gasification of plastics at the Energiewerke Schwarze Pumpe (ESPAG), in Bonn. Together with broken coal briquettes from brown-coal processing, the plastics are converted to gas by adding oxygen and steam.

d) Conversion of chloride based hard plastic into gasoline and heavy oil in Japan

Terazono (1994) reported that many Japanese companies have managed to turn non-chloride plastics, such as polyethylene, into petroleum fuels through heat processing. He added that, on the other hand, these companies are facing difficulties in breaking down chloride-based hard plastics, such as those used for computers and refrigerators, because the process gives off harmful hydrogen chloride gas as a by-product. Moreover, separating chloride and non-chloride based plastics takes time and is costly.

The demand for fedstocks recycling technology has risen in the first quarter of 1990s in Japan with the gradual decline in landfill space for garbage and rise in industrial waste, of which over 5% is plastics (Terazono, 1994). In 1990, Toshiba initiated a development programme for recycling chloride plastics, which account for 25% of all the country's plastic wastes. Its researcher at its environmental technology laboratory, set up to answer the government's call for industry's greater involvement in waste disposal, led the technology development. After two years of experimental work, it was discovered that adding a high-density alkaline solution when heating the chloride plastics turns the hydrogen chloride into a harmless salt (Terazono, 1994). The solution also removes plastic additives which prevent heat decomposition, and thus, increases the fuel obtained from the heating process. In addition, small metal parts which are difficult to detach from hard plastics do not need to be removed. Its development also solved the problem of having to separate chloride and non-chloride plastics. In the process of Toshiba's demonstration plant, the plastics are broken down into fuel, salt, soda and carbon dioxide. The prototype system produces more than 200 litres of fuel out of 250 kg of plastics in 11 hours. After the plastics are decomposed, pressures and temperatures in the combustion chambers can be adjusted to create several kinds of fuel, including heavy oil, kerosene and gasoline. The new technology can be applied to more than 90% of all plastic, the proportion that decomposes when heated.

Aside from the environmental benefits, there are also cost advantages. For example, Toshiba currently pays US$ 515 (£330 or Y50,000) to dispose of 1 tonne of industrial waste; since the company throws away 4,000 to 5,000 tonnes of plastic garbage a year, it could save up to US$ 2.6 M (Y250 M) a year by using the fuel reclaiming technology (Terazono, 1994). The company expects to market the system as a smaller and more durable device. The company believes that its system is appropriate for medical equipment makers and hospitals, which use large amounts of chloride plastics. The company has received enquiries from German and other European companies in plastic moulding and plastic board manufacturing industries. However, no latest information about any improvement of this technique has been found in the literature surveyed up to the present.

e) Logistics of feedstock recycling and practicable limits of recycling

Cost : For mixed plastic waste, logistics are particularly important. Most important issue is the cost of the recycling facility. According to one estimate from BP, a 50 M kg (110 M lb.) per year recycling plant would cost about US$ 20 M (Layman, 1993). If the product value is less than the cost, the difference is the gate fee. This fee has to be paid, whether with government subsidy, from levies on plastics sold, or in some other way. Therefore, the ultimate objective to the industry is to reduce the gate fee by making the process as cost efficient as possible. Shell's Arend Reininck, project leader, said from a technical standpoint that *"everything can be done but the question for any process is: Does it make sense from an economic view? Is it attractive? And is it robust enough to handle rubbish in mixed plastic waste?"* (Layman, 1993).

Number of units required: Shell Chemicals, which is working on feedstock recycling technology, has estimated that at least 40 units at 50 M kg per year each would have to be built by the year 2000 to recycle 10% of Europe's plastic waste (Layman, 1993). It believes that this figure represents the practicable limit to plastics recycling.

Optimal-sized plant and availability of waste: Layman (1993) reported that BP Chemicals has realised that the cost of plastics recycling can be minimised by establishing optimal-sized feedstock recycling plant and through providing sufficient amount of waste to feed the plant. It is also noted that the main limitation of this type of plant would be the

logistics in getting the waste to it. Capacity of an optimal-sized, lowest cost plant would be about 200 M kg (440 M lb.) per year, whereas only about 30 Mkg to 50 Mkg (66 Mlb. to 110 Mlb.) per year would be practical (Layman, 1993). It means that establishing a optimal-sized plant would be limited by the amount of the waste that could be collected from a practical radius of about 32 km, unless transport improves.

Locating recycling plant in urban areas - Geographical factors: The factors mentioned above imply that recycling facilities would need to be located in urban areas. This is because to support supply of 50 Mkg plastic waste per year would probably need about 5 M people to generate this amount of waste (Layman, 1993). As for construction cost, both BP and Shell agree that recycling facilities sited next to refineries make better economic sense. A stand-beside plant would halve the cost of trying to build a stand-alone 50 Mkg per year plant. Generally, people are also accustomed to a plant being located next to an oil refinery and so there will be lack of opposition to build a stand-beside feedstocks recycling plant.

2.3.3.2 Recycling of single plastic waste : Polymer Deconstructing

Chemolytic processes for recycling single-plastic waste have been present for many years. Many companies have developed their technology to deconstruct polymer waste using this process, to feed it back to production streams. While there is no single, easy way to recycle single grade plastic waste, chemolytic methods of recycling such plastics are reasonably straightforward.

a) Clothing made from recycled PET bottles: In the USA

Dyersburg, a US knitting company based in Tennessee, pioneered recycled fibres in the early 1990s with Wellman (the second-biggest US producer of polyester fibre) and Patagonia (an eco-conscious Californian technical clothing maker). Wellman had been using recycled polyester in its fibres since the mid-1960s, but the source was post industrial (Simonian, 1995).

In 1992, 2.5 M PET plastic soft drinks containers/bottles were consumed per hour in the USA, Simonian (1995) reported. In order to recover this resource, in 1993, Wellman

developed a new polyester fibre called 'EcoSpun' which contained 80% recycled PET (Simonian, 1995). The process needs to turn the plastic into a liquid, PET bottles are first cut up and then melted, prior to filtration to remove impurities and extrusion to form a fibre. Dyersburg spun it into yarn and knitted it into fleece for jacket making. However, as the new fibre received welcome from environmentalists, Wellman's market researchers said it had to reduce the denier (thickness) of the fibre and maximise its recycled content, in order to optimise its commercial prospects and also to ensure that quality would not be compromised by using ever more second-hand bottles. By August 1994, Dyersburg in co-operation with Wellman, produced the world's first yarn based on 100 per cent recycled PET (Simonian, 1995).

Wellman gets its bottles either from kerbside collection bins or directly from municipal recovery facilities in the US states operating obligatory recycling schemes. Wellman now has more than 100 customers and Dyersburg alone supplies 22 textile and clothing groups. Prices were relatively high until 1995 (Simonian, 1995). The recycled fleece was about 7-10 per cent more expensive than normal polyester fibre, but the difference was not necessarily passed on to the customer.

b) Recycled yarns made from PVC bottles: In France

Research was proceeding along much the same lines in France to develop recycled synthetic fibre from discarded PVC mineral waters bottles. Rhovyl, a specialist textile group, has recently started making yarn comprising 70% PVC and 30% wool (Simonian, 1995). About 80% of the bottles made in France are of PVC instead of PET as in the USA. As in the American PET recycling processes, French PVC bottle recycling processes also need to turn the plastic into liquid, but as PVC could not be melted down it has to be dissolved in a solution of acetone and carbon sulphate (Simonian, 1995). However, removing impurities is essential in both cases. Complex filtration to remove substances such as polyethylene caps and chemical additives to improve shock resistance, mean that production costs for recycled materials are higher than for virgin plastic.

Both Wellman and Rhovyl are confident about the future, but Rhovyl already has some more ideas: the thread could be used for a range of products, such as, socks, gloves or

blankets; or it could also be mixed with other yarns, such as mohair or silk, to make wholly new materials (Simonian, 1995).

c) Fleece jacket made from recycled PET: In the UK

The Brasher Boot company, a small British concern based in Cumbria, produced Europe's first fleece jacket made from recycled PET bottles. Most of the materials, except elements such as the zip and thread, were 100 per cent recycled. Recycled PET meets crucial quality of a jacket such as lightness, comfort, warmth and durability. The recent development of Brasher's Mountainmaster jacket is a breakthrough in Europe, and possibly the world, as previous products have used fleece with a maximum 80 per cent recycled content (Simonian, 1995).

d) Recycling of PET, urethane, Nylon and other polyesters: In Europe

In Germany: Recycling of PET and other polyesters has been a long time project at Hoechst in Frankfrut. It has the technology to recycle chemically PET bottles using the methanolysis process dating back to before 1978. At that time, no one was interested in the technology, because all virgin material was cheaper than recycled. Hoechst, through Hoechst Celanese, recently set up a venture with Coca-Cola Bottling Co., first in the US and then in the UK, to chemically recycle PET soda bottles using the methanolysis process (Simonian, 1995). Coca-Cola received necessary approval from the authority concerned to incorporate up to 25 per cent of recycled material into 2 litre bottles. The company is also looking at developing recycling of polyester fibre to feedstock, particularly for carpet fibre. It expects US mills to begin introducing carpets made of the fibre into the market.

In Ireland: Wellman International reprocesses used PET bottle into fibre at a plant in Ireland with a capacity of 27,000 tonnes per year. The company wants to produce Ecospun - a high quality fibre already made in the USA - in Europe. Its feedstock is virgin PET, industrial waste and used bottles. The plant's 10,000-12,000 tonnes per year expansion plan, which was due by 1995, will consume material from all three sources, but Wellman wants more used bottles, especially from the UK. The reasons are that the UK is the single biggest market for its fibres. The company wants to close the loop of discarded PET bottles for the UK. John Rice, Raw materials Purchasing Executive for Wellman

International, at a Recoup conference in November 1994, said, *"We are very disappointed to see only 1,000 tonnes of PET collected, coming from a market* (UK) *where 135,000 tonnes PET is used. The same quantity is returned from Iceland in one year - a return rate of 90 per cent from a population of 250,000"* (ENDS Report 238, 1994). According to both Recoup and the European PET recycling organisation (PETCORE), although plastic recyclers are desperate for more material to recycle at the present time, there is a shortage of collection systems which is limiting its growth.

2.4 Recycling Debate : Socio-economic and Environmental factors

Recycling is really just another method to reduce waste proliferation. Landfill sites throughout Europe, in particular, are reaching their capacity; there are limits to what can be done with mechanical recycling of polymer wastes. Citizens in many countries in Europe and in the US are opposed to incineration. Incineration with energy recovery is the method the industry strongly prefers. Municipal incinerators consume more than 70 per cent of the domestic waste in Denmark and Japan, and other countries are turning to this as the preferred method of disposal (New Scientist, 1991). In Britain, less than 10 % of household plastic waste ends up this way (APME, 1997). If this option is chosen, then the plastic part of waste becomes important because it helps in the incineration of other damp domestic rubbish. It has also been noted that plastic waste contains about the same amount of energy as the oil from which it came (New Scientist, 1991).

Most of plastics industries feel that the debate about recycling ignores some key aspects. For example, more than 95% of the world crude oil is used as fuel and only 4% is used by the virgin plastics manufacturing industries (Layman, 1993). Nevertheless, consumers are not ready to accept incineration of this 4% of a barrel of oil after having a variety of useful application of plastic products made out of the small proportion of crude oil. This is because plastic waste arouses strong emotions as often it appears to be present in such large amounts.

However, recycling is ranked low for its energy saving potential in a list of household energy efficiency measures identified by a report commissioned by Nuclear Electric, the

electricity generator, from the Centre for Social and Economic Research on the Global Environment at University College London, UK. Although recycling is *"one of the most well-known energy saving measures"*, the report says, it scores lower than the efforts of energy saving by insulating cavity walls and lofts, draught-proofing or putting reflective foil behind radiators (Maddox, 1994). Recycling the waste can be more harmful to the environment than incinerating it, because it has a hidden environmental cost. All the process involves energy use and add to pollution (Nicholson-Lord, 1994). Moreover, Lascelles (1994) pointed out the view of Mr. Dieter Burkle of Elf Atochem that 100 kg of plastic can replace 200-300 kg of metal in a car. He added that this weight reduction should save 750 litres of petrol over the life time of the car, which is a significant contribution to conserving resources.

It is claimed by some officials from the plastics industry that society will soon have to make a choice between degradable plastics and recycling of plastics. It means both cannot be exist at the same time. If recycle plastic is encouraged then it is necessary to prevent the waste being contaminated with photo-degradable or bio-degradable plastics. Major problems could occur in plastics recycling if items made from such materials contain degradable elements and break up in sunlight. Most plastic in Europe and the US ends up in rubbish tips. William Rathje of the University of Arizona, US has investigated rubbish sites and found that plastics account for less than 5 per cent by weight and 12 per cent by volume (New Scientist, 1991). He also finds that in the anaerobic conditions of such sites, fewer bacteria can thrive and so there is only slow degradation of paper and waste food, and almost none of plastics.

According to Michel Buzzacott, then chief executive of BP's polymer and olefins division, how far the plastic recycling industry goes will depends on the green conscience of Europe, but in the end, the consumer or the taxpayer will have to pay. This view is disputed, however, by the environmental lobby which accuses the plastic industry of deliberately exaggerating the cost of plastic recycling in order to obstruct regulatory moves (Lascelles, 1994). The industry could do much more, it urges, to reduce collection costs. Some environmentalists say that manufacturers of plastic containers should go further and design their products so that they are more readily reusable, doing away with recycling altogether.

In summary, according to Christian Troussier, chairman of the European consortium of five leading petrochemical companies, the most economic way of using waste plastic is to burn it as a fuel, but this is widely viewed as wasteful (Lascelles, 1994). He said that the least economical way is mechanical recycling, although that tends to be the most popular with the public. He added that feedstock recycling fits somewhere in the middle, and it is not as expensive as mechanical recycling, and on top of that, it has public acceptability to make it work (Lascelles, 1994). However, the potential significance of recycling plastics into feedstock is hampered by costs higher than those of other ways of dealing with plastic waste. He believes that up to two-thirds of the cost would have to be covered by a 'service fee'- in other words consumers would have to pay to have their plastics recycled, either voluntarily or through a levy.

2.5 Legislative Factors for Promoting Plastics Recycling

There is no legislation or government policy directly related to plastic recycling available either in Bangladesh or India, but a great success has already been achieved by both countries in their mechanical recycling of plastic waste using manual collection, sorting and washing methods, followed by processing with the help of semi-mechanised equipment. On the other hand, there are high hopes for recycling plastics in Western Europe forced by legislation and national governments' recycling policies and targets, but several hurdles are slowing progress of recycling in these countries.

2.5.1 In Western Europe

Several EU (European Union) members are close to implementing the European Commission (EC) Packaging and Packaging Waste Directive (Luesby, 1996). Before this directive, there was no EC legislation which could have been applied directly to the recycling of plastics (CRISP, 1994). This Directive requires to recover 50-65%, with a recycling target of 25-45% and with a minimum of 15% for each material by 2001 (DoE, 1995; Boulton, 1995). In addition, it was expected that within 5 years after the Directive comes into force, all nonreusable/recoverable packaging will be banned and all plastic packaging will have to adopt a standard identification system (CRISP, 1994).

This legislation was introduced with the intention that it will encourage recycling and reduced packaging (Mumma, 1995; DoE, 1995). However, on the other hand, although their national schemes are launched to meet the requirements of the directive (Table 2.6), plastic recycling remains fraught with commercial and technological difficulties (Luesby, 1996). Moreover, here it is important to notice that there is a large difference in the targets of packaging waste recovery (50-65%) and recycling (25-45%) set in by the Directive. Moreover, no specific packaging minimisation targets have been set. What would be the ultimate fate of the waste to be recovered but not recycled? In this respect, therefore, Ogilvie (1995) reported that effects of this EC directive will alter the economics of waste collection and utilising the waste as a raw material.

2.5.2 In Germany

The Packaging Waste Ordinance (1991) in Germany, has introduced a 64 % recycling quota for plastic, and it has also implemented a mandatory deposit-refund system for all plastic beverage containers. In the subsequent years, the ordinance has observed two amendments (Table 2.6). In 1995, the first amendment for the ordinance has called for at least 50% mechanical recycling of plastic to ensure recycling activity, followed by the draft amendment in 1996 which targeted 60 per cent recycling quota for plastic and compounds along with aluminium and paper due to come into effect from January 1998 (Bontoux and Papameletiou, 1996). The ordinance has resulted in people returning product packaging for recycling to the shops where the goods had been bought (Cowe, 1995; Bayer,1998). Following this requirement to accept returned packaging, the DSD was created in 1991, which is sustained by businesses because they do not want to set up their own systems for handling returned packaging.

Finally, however, the system has now succeeded in collecting, separating and recycling substantial proportions of paper, card, plastic and other materials. The most difficult of all materials to recycle is plastic packaging. A more significant measure of success from the environmental point of view is that the volume of packaging material used has fallen over the past few years (APME, 1997). According to DSD, 1 M tonnes less material was used in 1993 than in 1991. That represents a reduction of 15 kg per person or almost

Table 2.6: Legislation on Plastic Recycling and Its Effects in EU, Germany and the UK.

Region /Country	Legislation	Aims	Description of the cases	Critical Points/ Effect of Legislation: Economic Operators and Instruments
EC	Directive 94/62/EEC	Packaging Directive 94/62/EEC in favour of prevention, reuse and recovery.	The Packaging and Packaging Directive 94/62/EEC prescribed minimum and maximum recycling targets for packaging waste promoting the prevention, reuse and recovery of resources. Between 25 and 45 % of the packaging waste have to be recycled by the year 2001, with a minimum of 15% for each packaging material.	Almost all EU member states have already reached the required minimum recycling targets, for each packaging material, excluding plastic. Waste exported for recycling will not count towards the 15% recycling target for each of the material considered.
Germany	Packaging Waste Ordinance (1991)	Different quotas for different recyclable materials to promote recycling. Refillable beverage container quota to promote reuse.	72% recycling quotas for glass, aluminium and paper, 64% for plastic and compounds. A mandatory deposit-refund system for all plastic beverage containers is implemented if recycling quotas (Art. 6 annex) are not achieved and if the quota for refillable beverage containers falls below 72%.	Incompatible with EU Packaging Directive targets (D94/62). No rationale for favouring re-use vs. recycling.
Germany	Draft amendments to the Packaging Ordinance (1991).	Quotas for mechanical recycling for plastic to ensure recycling activity.	The amendments for Packaging Waste Ordinance call for at least 50% mechanical recycling of plastic. Date of amendments is 20.12.95	Technical difficulties to reprocess impure material and market deficiencies for recycled material.
Germany	Packaging Ordinance 1996 draft amendment	A new reduced quota for recycling to address the practicality of existing recycling opportunity.	From January 1998: 60% recycling quotas for aluminium, paper, plastic and compounds (draft amendment) Material covered: Transport packaging, sales and secondary packaging with dangerous goods (Draft)	'DSD' system responsible for collection, sorting and recovery of used packaging. DSD is financed by a fee per packaging (weight and volume dependent).
United Kingdom	Environmental Protection Act 1990	Recycling Credit Scheme in favour of recycling or recycling infrastructure	A recycling credit scheme covering the full long marginal cost of disposal has been set up in the UK since 1992. The average of value offered as a credit was in 1992/93 US$ 8 (ECU 7.3) per tonne.	After the implementation of the scheme, recycling increased by 3.9% in 1991/92 and 5% in 1992/93.
United Kingdom	White Paper on the Environment Industry proposal	All packaging wastes are covered and given a recycling target to exploit value from waste materials as much as possible.	50% of readily recyclable materials in household waste to be recycled by the year 2000, which amounts to 25% of all household waste (white paper). 58% of packaging recovery by the year 2000: Paper 66%, Glass 57%, Aluminium 52%, Steel 37%, Plastic 16% (Industry proposal)	Packaging levy: Shared responsibility- Valpack. Shared 'First Use' (responsibility to the organisation that makes first use of packaging products). Landfill tax (average amount of US$ 5.8 (ECU 5.3) per tonne.

Sources: Bontoux and Papameletiou, 1996; Waite, 1995; CRISP, 1994; Gandy, 1993; and Bayer,1998.

one-tenth of what was in use. In March 1995, it opened 200 recycling centres across the country to show the public how the process works and try to make it work better.

2.5.3 In the UK

The current UK legislations which applies to the recycling of plastics are: the Control of Pollution Act 1974 (CoPA 74), the Waste Regulation and Disposal (Authorities) Order made under the Local Government Act 1988, the Environmental Protection Act 1990 (EPA) (Parts I & II), and the White Paper on the Environment (DoE, 1995; Garbutt, 1995; Tromans, 1996). Section 52 of the Environmental Protection Act 1990 on 'Waste Recycling Credits' set the framework for a system of payments to encourage the diversion of recyclable materials from the domestic waste stream (Bates, 1992; Tromans, 1996). The credit scheme has been set up since 1992, to cover the full long marginal cost of disposal. Bontoux and Papameletiou (1996) pointed out that the average of value offered as a credit was in 1992/93 US$ 8 (ECU 7.3) per tonne. They added that the scheme caused a small increase in the recycling rate of 3.9% in 1991/92 and 5% in 1992/93, and no clear correlation has been established between the scheme and recycling rate. It has also been mentioned that, however, almost 60% of the waste disposal and collection Authorities believe recycling would be lower without credits.

The UK Government in the White Paper on the Environment has covered all packaging wastes and has set targets to recycle 50% of readily recyclable materials in household waste by the year 2000, which amounts to 25% of all household waste (Bontoux and Papameletiou, 1996; CRISP, 1994). In lieu of this, the UK Packaging Industry proposal is to recover 58% of packaging waste by the year 2000: paper 66%, glass 57%, aluminium 52%, steel 37%, and plastic 16%. In order to encourage greater recycling of waste, the legislation has introduced a number of economic operators (such as 'Shared Responsibility' and 'Shared First Use Responsibility' to the organisation that makes first use of packaging products) and economic instruments or measures (such as 'Recycling Credit Scheme,' 'Packaging Levy' and 'Landfill Tax'). Landfilling waste has grown more expensive in recent years because of local opposition and because they are becoming scarcer. The costs of disposal are now US$ 12.5-18.7 (£8-£12) a tonne and the landfill levy adds US$ 3-8 (£2-£5) a tonne extra with this cost of disposal (Nicholson-Lord and

Hellier, 1994). Finally in December 1994, the UK government has adopted the EU Packaging and Packaging Waste Directive (DoE, 1995). In view of the ever changing local recycling infrastructure, the Government favours a voluntary approach, and will continue to work with voluntary groups to encourage innovative approaches to waste minimisation and waste re-use. All necessary encouragement will be directed by the Government to private business and the local authorities to work in partnership with the community and voluntary sectors to ensure optimum use of resources, and expertise (DoE, 1995).

Miguel Pestana of Waste Management International, one of the largest operators of landfill sites in Britain, does not think that landfill tax will have positive environmental effects that have been projected. He believes that the results could be reverse - the tax could well stimulate the use of substandard landfill disposal options and does not address the environmental performance of landfills (Nicholson-Lord and Hellier, 1994). However, under the Government's voluntary approach, each of the individuals is not directly responsible for his/her waste, and thus, co-ordination can be lacking, targets do not have to be met, and no one will be penalised if the target is not fulfilled.

Currently, reduction, minimisation and lightweighting are taking their place alongside recycling. *"Reducing packaging at source is more economical than recycling it at the end"*, said Tony Montrone, an environmental consultant with Arthur D Little in Boston, USA (Buckley, 1995). He added, *"although reducing packaging means lowering the cost of the product, but collection and recycling of the waste would add cost which the consumer is always going to pay for one way or another"*.

CHAPTER 3:

Fieldwork in Bangladesh and India

3.1 Introduction

Since problems of solid waste disposal and recycling are inherently related to densely populated urban centres, direct observations of the plastics recycling activities and working units within the municipal area of the cities of Dhaka, Calcutta and Delhi were performed. A five month fieldwork programme during November 1995 to March 1996 was undertaken in Dhaka for collecting fresh information and field data, searching the relevant literature and conducting moulding of sample jerry-cans. Having completed all necessary fieldwork jobs and sample products moulding using both virgin and post-user High Density Polyethylene (HDPE) in Dhaka, trips were made to the two densely populated Indian cities of Calcutta and Delhi in April, 1996, in order to investigate current status of plastics recycling in these cities in comparison to the operations in Dhaka. Completion of all these necessary attempts took two months extra than was anticipated at the beginning of the fieldwork. This was mainly due to political crisis and unrest during the fieldwork period in Dhaka which seriously affected the pre-designed fieldwork programme.

3.2 Case Study Methods: Dhaka, Calcutta and Delhi

Different methods were followed for collecting information, as appropriate. All relevant libraries, export-import bureau, information record keeping divisions of the government and non-government offices were visited and appropriate persons at the venues were contacted. All available relevant information gathered was stored with proper reference notes.

To design the main part of the case studies in these cities, direct investigations were made. First of all a feasibility study was carried out on their plastics markets for both virgin and recycled products, along with investigating the post-user plastic waste streams, in order to understand the fate of different batches of HDPE wastes. Attention was focused basically on HDPE wastes arising from domestic, hospital, industrial, commercial, and institutional premises.

An attempt was made during field observation to identify the locations of different operations in the recycling chain and the nature of the plastic waste recycling streams. Major plastics recycling units in all three cities were visited and careful observation made of the operations concerned and the workers interviewed informally, as appropriate. A number of visits were also given to virgin HDPE articles manufacturing industries. This was aimed at elucidating the precise nature of each operation, the type of person involved, the items being recycled, the types of plastic involved, and successive stages in this waste stream. An informal interviewing method was chosen because such an approach is easy and rapid in the context of the Bangladeshi and Indian social structure for communication between interviewer and interviewee, because workers are mostly illiterate and thus usually have a low level of comprehension and hesitate to disclose information to strangers.

In the case of Dhaka, a total of 270 persons were interviewed informally - 30 people from each of the groups of waste pickers, waste merchants, sorter-cum-washers, shredders, pelletisers / agglomerators, moulders, shop keepers (of virgin / recycled plastic flakes / pellets), and shop keepers of recycled plastic products. The major thrust of interviewing them was to explore: Are they able to differentiate different batches of HDPE general scraps and their number of processings? Which general scrap (given) has been processed previously how many times? How can they identify their processing number and what basis? What colour does a particular batch of scraps usually have according to their number of processings? Why are plastic processors required to use colour pigments with their feedstocks? Is there any tradition or common pattern in using colour pigment followed by the recyclers over the years? What are their opinions about quality degradation of recycled plastics? What are the factors affecting their quality?

Considerable periods of time were required at this stage to cope with the difficulties and complexity in identifying and differentiating a large variety of waste HDPE materials present in the plastic waste streams, and then, to select and collect a number of representative batches of HDPE feedstocks. These batches were collected on the basis of their number of times of previous processing, which were used subsequently in moulding sample jerry-cans following in-house successive reprocessings. Details of moulding methods are explained partly in the latter part of this chapter and in Chapter 5.

3.3 Results from the Case Study in Dhaka

Figure 3.1 shows the different socio-economic, human and environmental factors involved in plastic waste recycling in the metropolises of Bangladesh and India. Results from the questionnaire surveys and also from direct observations have confirmed that different types of post-user plastic waste are recycled in a large scale in these metropolises due to the opportunities resulting mainly from the presence of low cost-unhygienic-collection systems, a large market for both recyclable materials and recycled products, and a lack of public awareness and regulatory measures.

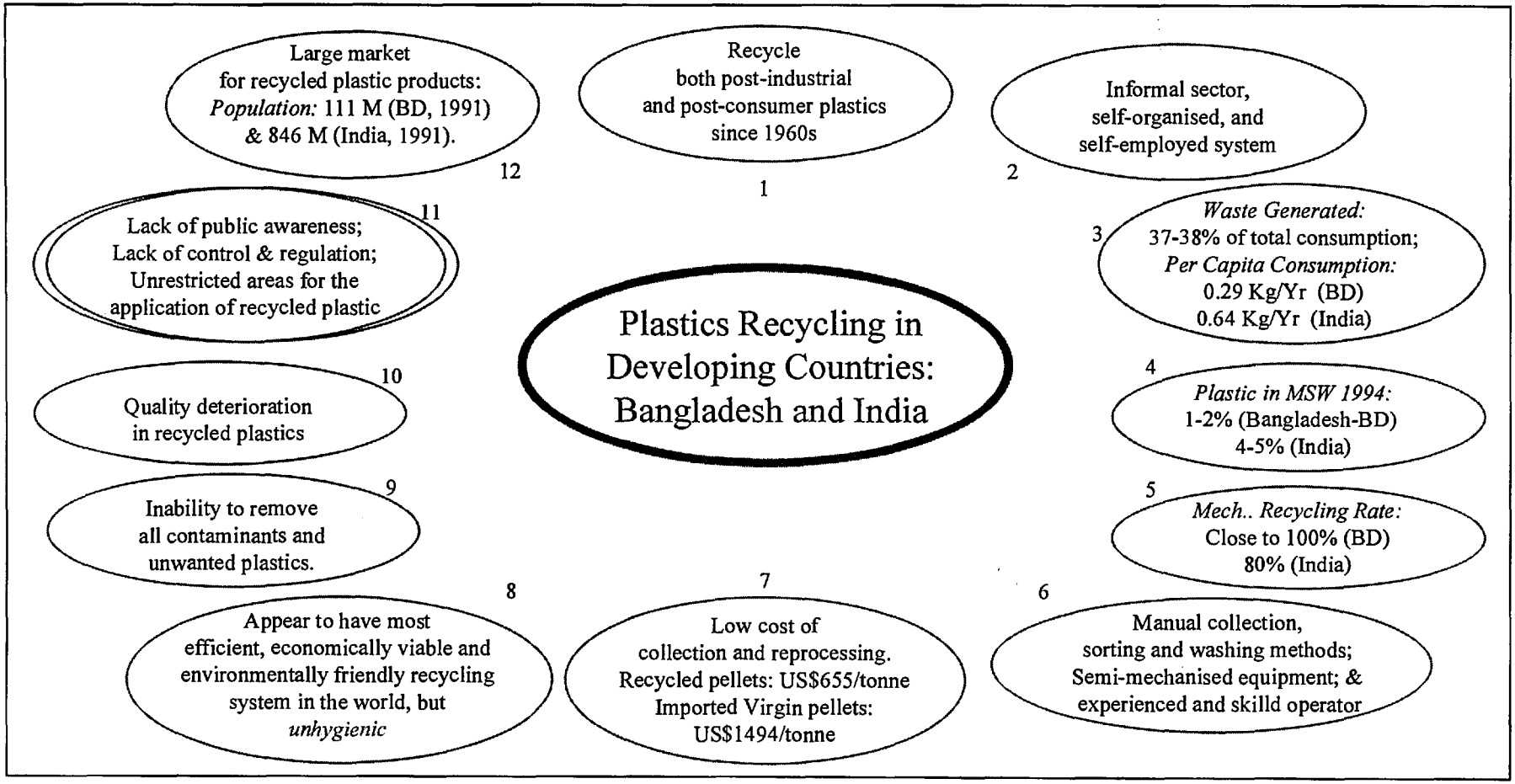
Jerry-cans (e.g. milk jugs like the containers shown in Photograph 2.2c in Chapter 2) are the most common HDPE product frequently used by the household consumers. These are usually made of both virgin as well as recycled materials. Table 3.1 shows a breakdown of recycling costs for 1 kg of HDPE waste. A total of US$ 1.45 was required from collection up to producing 15 nos. of 2 litre jerry-cans out of 1 kg HDPE recyclates in the economic context of Bangladesh in 1996. Break down costs are shown in Bangladeshi currency, "Taka (TK)".

Table 3.1: Cost of recycling for production of 15 x 2 litre jerry-cans out of 1 kg HDPE recyclates in the economy of Bangladesh. [US$ 1 ≈ TK. 41.5 (April 96)].

Cost factors	Cost unit	Range of unit cost (in Taka)	Average unit cost (in Taka).	Unit cost with added marginal value (TK.)	Unit cost with added marginal value (TK.)
Collection cost or primary value of waste	kg	2.00--39.00	17.00	17.00	17.00
Transporting a kilogram of plastics	kg/km	0.35 -- 0.08	0.22	17.22	17.22
Sorting	kg	0.37 -- 0.44	0.41	17.63	17.63
1.0-2.5% loss at sorting on the value of waste transported at sorting unit	kg	0.18 -- 0.45	0.32	17.95	17.95
Shredding	kg	0.66 -- 0.99	0.83	18.78	18.78
0.5-0.6% loss at shredding on the value of sorted waste	kg	0.09 -- 0.11	0.10	18.88	18.88
Washing	kg	4.40 -- 4.84	4.62	23.50	23.50
5-10% loss at washing on the value of flakes	kg	0.92 -- 1.85	1.39	24.89	24.89
Pelletising/Agglomerating	kg	2.20 -- 2.42	2.31	27.20	27.20
Moulding operator's wage	kg	5.85--12.00	8.93	36.13	36.13
Electricity bill for running moulding machine	kg	10.20	10.20	46.33	46.33
Manufacturer's profit	kg	7.50--20.00	13.75	60.08	60.08
Total cost required to recycle 1 kg of HDPE waste [or Company price of 15 nos. of 2 litre (or 2 nos. of 24 litre) jerry-cans*]:				TK. 60.08 ≈ US $1.45	

Notes: *15 x 2 litre or 2 x 24 litre jerry-cans can be made out of 1 kg recyclates/feedstocks. Moulding operator charge ranges from TK. 0.40 to 6.00 per production of 2 to 24 litre jerry-cans respectively. Cost of electricity required to mould 1 kg feedstocks into 15 x 2 litre jerry-cans = 0.194 unit x 15 nos. x TK. 3.5 = TK. 10.20.

Figure 3.1: Attributes and factors involved in plastic waste recycling in the metropolises of Bangladesh and India.



Data Sources: Questionnaire survey, 1996; Bhandare and Mukhopadhyay, 1996; BBS, 1996; Haque et al, 1997; Sarker, et al, 1995; Birley and Lock, 1997; EEP and IES, (undated); Fernandez, 1997; Haque and Bell, 1998; Ganguli, 1995; Ratra, 1994.

Service life spans of different household articles made of virgin HDPE were estimated on the basis of the responses from 100 housewives interviewed informally in Dhaka and shown in Table 3.2.

Table 3.2: Service life of different HDPE plastic articles in the developing economic context of Bangladesh.

Name of articles[1]	Sizes or quality[2]	Range of service life lengths	Average service length	Overall average
Carrier bags	All sizes	1 hour --1/2 year	0.08 year	
Mugs	All sizes	1 -- 3 year	1.5 year	
Buckets	All sizes	1 -- 5 year	2.8 year	
Bowls	All sizes	1/2 -- 6 year	2.6 year	
Jerry-cans *(Gallons)*	Small: 1001-- 5000 ml	1/6 -- 7 year	1.7 year	
	Medium: 5001--10000 ml	1 -- 7 year	3.7 year	
	Large: 10001--15000 ml	3 -- 8 year	4.9 year	
	V. large: >15000 ml	2 -- 6 year	3.7 year	
Containers *(Boiyum)*	V.V. small: <50 ml	7 days -- 1 year	0.3 year	**2.9 year**
	V. small: 50--1000 ml	1 month-- 5 year	2.5 year	
	Small: 1001--5000 ml	1 -- 5 year	3.5 year	
Water pots *(Badna)*	Good quality	2 -- 5 year	3.2 year	
	Poor quality	1 -- 2 year	1.4 year	
Bottles	V. small: 50-- 1000 ml	1 day -- 1 year	0.5 year	
	Small: 1001--5000 ml	1/2 -- 2 year	1.3 year	
Baskets	All sizes	6 month-- 2 year	0.9 year	
Furniture	All sizes	1-- 4 year	2.0 year	

[1] Typical local name of articles are in *italic* font.

[2] Scale for article's sizes: # Very very small = <50 ml # Medium = 5001 -- 10000 ml
Very small = 50 -- 1000 ml # Large = 10000 -- 15000 ml
Small = 1001 -- 5000 ml # Very large = >15000 ml

According to the quality desired by the consumer and the existing general practice of recycling, plastic recyclers in Dhaka mix higher grade HDPE feedstocks with lower grade HDPE feedstock in different proportions as shown in Table 3.3. They follow this method to maintain and also improve the quality of their recycled products above that which would produced if 100% lower grade feedstocks been used.

Table 3.3: Ratios followed in mixing lower and higher grade HDPE feestock, either before pelletising or moulding, depending on the quality desired, in Dhaka.

Products' quality desired	Proportion of lower grade feedstocks	Proportion of higher grade feedstocks
Marketable quality	50%	50%
Moderately good	40%	60%
Reasonably good	20%	80%
Very good	0%	100%

Table 3.4 shows a steady increase in annual imports of all categories of virgin plastics. A total of US$ 121×10^6 worth of plastic was imported in 1994-95, which is about 12 times greater than the imports in 1985-86 (Table 3.4). For the purpose of mathematical modelling (in Chapter 6), PE imports during 1990-91 to 1994-95 recorded in terms of monetary values (US$) have been converted into amount (in Mkg), using their average unit cost of imports (US$/kg). In the case of unavailability of published data, these unit costs were determined on the basis of the results obtained from interviewing informally 10 major plastic importers in the old Dhaka city.

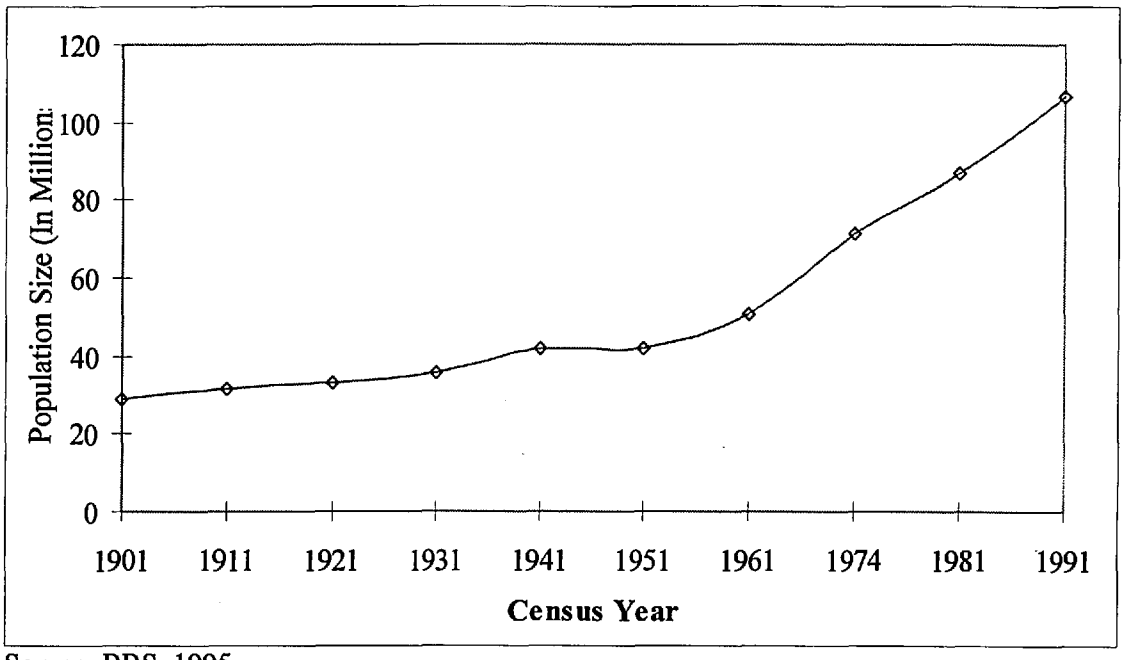
Table 3.4: Trend of annual importation of different virgin plastic pellets into Bangladesh (Import data units: US$ x 10^6).

Year	PE (LDPE + HDPE)			PP	PS	PVC	PVA	Other[1,3]	Total
	Imports[1] ($ x 10^6)	Average import price[2] (US$/kg)	**Imports** (Mkg)*	imports[1] ($ x 10^6)	imports[1] ($ x 10^6)	imports[1] ($ x 10^6)	imports[1] ($ x 10^6)	imports ($ x 10^6)	imports[3] ($ x 10^6)
1985-86	---	---	---	---	---	---	---	---	10.03
1986-87	---	---	---	---	---	---	---	---	11.83
1987-88	---	---	---	---	---	---	---	---	20.69
1988-89	---	---	---	---	---	---	---	---	25.63
1989-90	---	---	---	---	---	---	---	---	27.09
1990-91	11.45	1.57	**7.29**	5.00	0.94	6.64	1.23	17.59	42.85
1991-92	15.49	1.62	**9.56**	7.63	1.33	8.62	1.67	21.28	56.01
1992-93	12.12	1.62	**7.48**	5.77	1.50	12.05	2.29	31.17	64.90
1993-94	16.45	1.61	**10.27**	8.24	2.54	16.50	3.43	36.05	83.29
1994-95	25.35	1.46	**17.36**	13.57	3.99	20.89	4.90	52.05	120.75

Notes: "---" = Break down of imports data were not available. US$ 1 ≈ TK. 41.5 (April 1996).
*Imports = Imports (in US$ x 10^6) ÷ Import price (in US$/kg).
Data sources: [1] BB, 1996b (Personal communication); [2] Informal questionnaire survey in the Dhaka plastics market (March, 1996). [3] BB, 1996c; BB, 1994; BB, 1992; and BB, 1991.

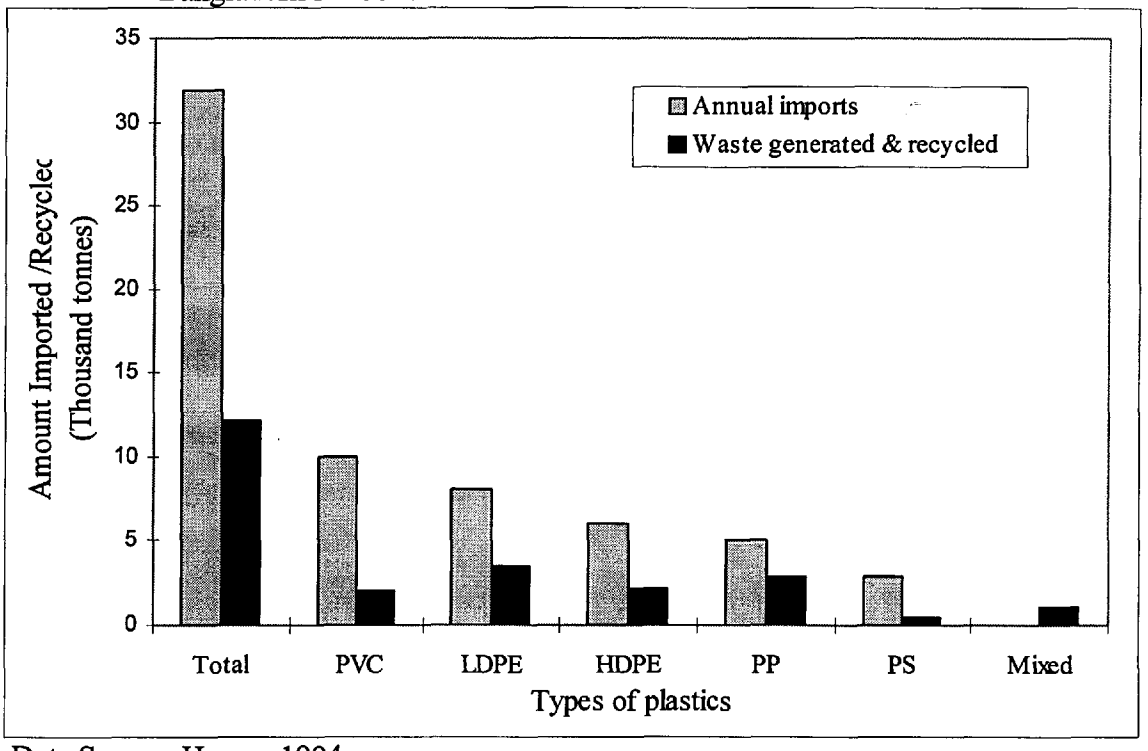
Along with the country's cultural and economic development as reflected by the steady increasing trend of plastic imports and consumption over the last few decades, the rapid growth in population size (Figure 3.2) is certainly a vital factor resulting in a higher demand for commodity products such as household plastic products. Since the country does not produce virgin plastics, it has to import a huge amount of plastic pellets to meet the demand.

Figure 3.2: Population growth in Bangladesh, 1901-1991.



Source: BBS, 1995.

Figure 3.3: Comparison between the amount of plastics imported and recycled in Bangladesh in 1994.



Data Source: Haque, 1994.

In 1994, a total of 12.1 Mkg plastic waste were generated and recycled in Bangladesh, which was equivalent to 38 % of the total imports (31.9 Mkg) in that year (Figure 3.3 and Table 3.5). The rest (62 %) mainly remained in use, and were partly disposed of and/or exported (Table 3.5). Rate of discarding of plastics products was high in the case of those produced from PP (58 %) and LDPE (44 %) due to their short service life compared to other plastic products. Lower discarding rates were experienced for PS (15 %). This is because PS was generally used in producing some more useful items in this developing country rather than producing disposables as in the developed countries.

Table 3.5: Imports of thermoplastics, estimated amount of waste generated and recycled, and proportions of imported plastics recycled in Bangladesh in 1994.

Types of thermo-plastics	Amount of imported plastics[1] (Tonne)	Estimated amount of waste generated and recycled[1] (Tonne)	Amount recycled (in % to imports)	% of imports mainly remained in use, and partly disposed of and/or exported
PVC	10,000	2,043	20.43	79.57
LDPE	8,000	3,541	44.26	55.74
HDPE	6,000	2,123	35.39	64.61
PP	5,000	2,940	58.80	41.2
PS	2,900	445	15.33	84.67
Mixed	----	1,040	----	----
Total	**31,900**	**12,132**	**38.03**	**61.97**

Notes: PVC = polyvinyl chloride, LDPE = low density polyethylene, HDPE = high density polyethylene, PP = polypropylene, PS = polystyrene.
[1] Data source: Haque, 1994.

3.4 Methods of Sample Collection and Moulding

3.4.1 Characterisation and Collection of Sample Materials

Characterisation, identification and collection of all different HDPE feedstocks for the purpose of moulding them into sample products were based on the following characteristics of the plastic recycling system in Dhaka:

(a) Each recycling cycle starts with collection of discards, then follows a number of processing stages (sorting, shredding, washing, and pelletising/ agglomerating), and ends with moulding (manufacturing). Then recycled products are marketed for use, which will be used up, discarded and collected for next recycling. This means that each step of reprocessing plastics involves at least two successive melting or processing steps i.e. pelletising / agglomerating and moulding. However, this number of processing steps within a single recycling cycle increases as the materials

move on to higher numbers of recyclings. As a result, if a batch of plastics has already been recycled 5 times (i.e. passed 5 recycling loops), it is more likely that the batch experienced 13 or 14 processing / melting steps (Figure 3.4).

(b) When a new plastic product made of virgin pellets (denoted as Pro-0) is discarded after its useful service life in use and reuse, it will undergo most probably at least six successive 'closed-loops' identified in the existing recycling system of post-user plastic waste in Dhaka as shown in Figure 3.4. Over these successive recycling loops, any batch of virgin plastic products after their discarding are usually found to have the following increasingly darker colours as they are recycled again and again with increased number of processings: transparent / translucent / white ⇒ low grade translucent / white ⇒ off white / yellow / red / green / blue ⇒ brown / dark green / dark blue ⇒ dull brown / dull green / dull blue ⇒ black ⇒ dull black ⇒ very dull black (Figure 3.4).

Identifying the number of recycling loops and recycled products' colour changing patterns was based on the results obtained from interviewing 270 recyclers involved at different stages of the activity (already mentioned earlier in this chapter). These results were coupled with comprehensive understanding of how changes in external appearance and colour of recycled plastic products occurred over the course of successive recyclings. This understanding was based on earlier experience of the system by the present researcher for more than a decade, and was also confirmed by the information obtained from the recyclers in Dhaka.

With some exceptions associated with waste pickers, it was recognised by most of the plastics recyclers interviewed in Dhaka that deterioration in colour, external appearance, and the overall quality of recycled plastic products occur very often at each cycle of successive recyclings due to the effects resulting from a number of factors. These factors include: (i) repeated processings of plastics using manually operated recycling machines which sometimes cause overheating and longer retaining time effects, (ii) level of exposure to sun light during their service life,

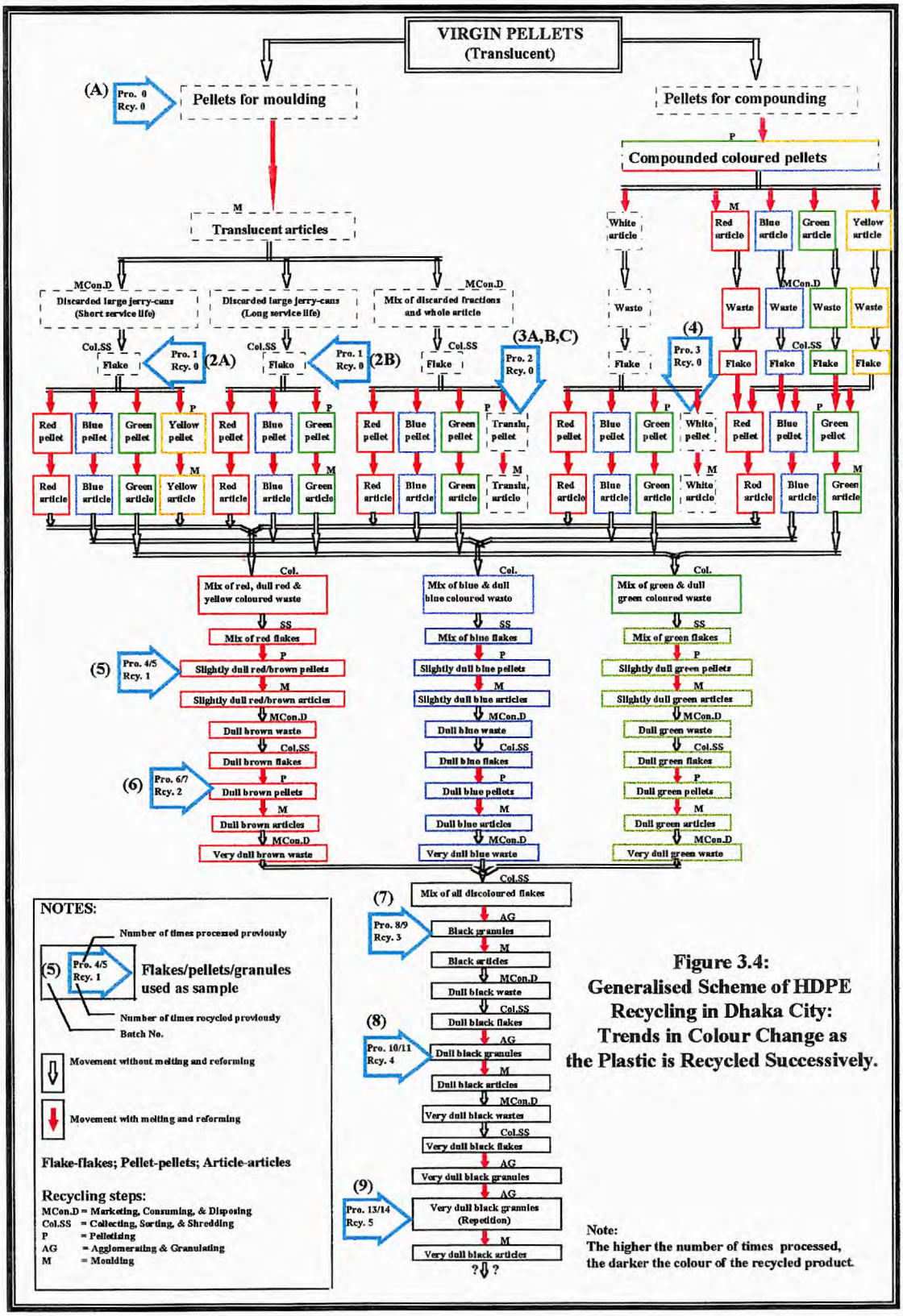


Figure 3.4: Generalised Scheme of HDPE Recycling in Dhaka City: Trends in Colour Change as the Plastic is Recycled Successively.

Note:
The higher the number of times processed, the darker the colour of the recycled product.

and (iii) presence of extraneous contaminants inevitably added into feedstocks. In order to make external appearance of recycled products attractive, plastics recyclers in the city use increasingly darker colour for their feedstocks processed higher number of times.

Since almost the same recycling practice, especially in the case of colour use, is being followed traditionally by all recyclers in Dhaka, the entire system can be termed as "plastics recycling scheme" (Figure 3.4).

(c) It has already been mentioned that the higher the number of times of recycling performed, the higher the number of processings which have to take place within a particular recycling loop. This is due to the fact that increasing amounts of impurities are naturally included into feedstocks as the materials have previously undergone several times for successive 'production-consumption' processes. Thus these impurities are generally screened out by putting back the feedstocks repeatedly into a processing extruder and passing through a number of filters set in the extruder's barrel. Irrespective of number of times processed, any batch of waste materials is washed manually only once after cutting into flakes.

Therefore, all these facts were carefully evaluated when choosing a representative batch of HDPE feedstocks from the Dhaka plastics market. Specific attention was given to their background history, particularly the number of times processed previously under the existing recycling system (Figure 3.4).

3.4.2 Preparation of Feedstocks

Bearing in mind the understanding obtained from the existing plastics recycling scheme (as shown in Figure 3.4), 9 different batches of representative HDPE plastic waste were collected from the Dhaka plastics market. A total of 12 different category of feedstocks were prepared out of these 9 batches, according to their 'number of times processed previously' and 'level of impurity contents as generally estimated visually' (Table 3.6). Sample feedstocks collection and preparation were designed in such a way that different batches of feedstocks had different numbers of times of processing, ranging from zero to thirteen / fourteen times. In order to meet this requirement, some of the sample

Table 3.6: Notations of the samples produced from 9 different batches of HDPE feedstocks (12 categories) through successive in-house reprocessing (moulding and then shredding into flakes to give feedstocks) using a locally produced single screw extrusion-blow-moulding machine in Dhaka.

Number of times processed within the factory premise	**Description of the Feedstocks and Their Position According to the Number of Times Processed in the Real Environment**											
	Translucent virgin (round) pellets : **Pro.– 0 Rcy.– 0**	Translucent flakes (of short life /large/ whole /single type of waste articles) : **Pro.– 1 Rcy.– 0**	Same waste stream of [2A] but long life /large/ whole /single type of waste articles): **Pro.– 1 Rcy.– 0**	Pellets (of short & long life translucent discarded articles & fractions): **Pro.– 2 Rcy.– 0**	Same batch of [3A] but washed twice & colour flakes removed before pelletising: **Pro.– 2 Rcy.– 0**	Same batch of [3A] but chaff won before pelletising: **Pro.– 2 Rcy.– 0**	Pellets made of milky coloured waste: **Pro.– 3 Rcy.– 0**	Granules made of brown coloured wastes: **Pro.– 4/5 Rcy.– 1**	Granules made of dull-brown coloured waste: **Pro.– 6/7 Rcy.– 2**	Granules made of black coloured waste: **Pro.– 8/9 Rcy.– 3**	Granules made of dull-black coloured waste: **Pro.–10/11 Rcy.– 4**	Granules made of very dull-black coloured waste: **Pro.–13/14 Rcy.– 5**
Batch No. →	(1)	(2A)	(2B)	(3A)	(3B)	(3C)	(4)	(5)	(6)	(7)	(8)	(9)
Pro. 0	Pel. (1)/0											
Pro. 1	(1)/1	Fla.(2A)/1	Fla. (2B)/1									
Pro. 2	(1)/2	(2A)/2	(2B)/2	Pel. (3A)/2	Pel. (3B)/2	Pel. (3C)/2						
Pro. 3	(1)/3	(2A)/3	(2B)/3	(3A)/3	(3B)/3	(3C)/3	Pel. (4)/3					
Pro. 4	(1)/4	(2A)/4	(2B)/4	(3A)/4	(3B)/4	(3C)/4	(4)/4	Gra. (5)/4				
Pro. 5	(1)/5	(2A)/5	(2B)/5	(3A)/5	(3B)/5	(3C)/5	(4)/5	(5)/5				
Pro. 6	(1)/6	(2A)/6	(2B)/6	(3A)/6	(3B)/6	(3C)/6	(4)/6	(5)/6	Gra. (6)/6			
Pro. 7	(1)/7	(2A)/7	(2B)/7	(3A)/7	(3B)/7	(3C)/7	(4)/7	(5)/7	(6)/7			
Pro. 8							(4)/8	(5)/8	(6)/8	Gra. (7)/8		
Pro. 9									(6)/9	(7)/9		
Pro. 10										(7)/10	Gra. (8)/10	
Pro. 11											(8)/11	
Pro. 12											(7)/12	
Pro. 13												Gra. (9)/13
Pro. 14												(9)/14

Notes for the Table 3.6:

Pel. (2A)/2	--Sample feedstocks have been processed previously several times under the existing recycling system.
(2A)/3	--Sample products which have experienced the direct effect of the real environment (involve the factors associated with the existing recycling system and the tropical environmental conditions present in Bangladesh) on their properties.
(2A)/4	--Sample products which have experienced diminishing effects of the real environment and increasing effects of in-house successive recycling on their properties.
	--No further successive reprocessing was carried out due to the shortage of time and resources required.

Pro. - processed, Rcy. - recycled, Pel. - pellets, Fla. - flakes, Gra. - granules
Note for notations: (3A)/5 = (Batch number, sub-category number) / Number of times processed.
Determining the position of a feedstock or a sample product in Table 3.6 involves co-ordination between the 'number of times processed under the current system' and 'number of times processed within the factory premises'.

Photograph 3.1: Representative sample HDPE feedstocks collected from the Dhaka:

1/ Virgin translucent pellets, (1)/Pro-0;
2A/ Translucent rod pellets, (2A)/Pro-1;
3A/ Translucent rod pellets, (3A)/Pro-2;

4/ Milky coloured rod pellets, (4)/Pro-3;
5/ Brown coloured granules, (5)/Pro-4,5;
6/ Dull brown coloured granules, (6)/Pro-6,7;

7/ Black coloured granules, (7)/Pro-8,9;
8/ Dull-black coloured granules, (8)/Pro-10,11;
9/ Very dull-black coloured granules, (9)/Pro-13,14.



batches were in pellets, some were flakes, and others were agglomerated granules (Photograph 3.1) due to the lack of feedstocks processed previously different number of times but available in a homogeneous form in the Dhaka plastic market at the period of collection. Considering a minimum requirement to feed and run a single screw extrusion-blow-moulding machine (Figure 3.5 and Photograph 2.2a) and to produce a total 140±10 nos. of jerry-cans [2 litre in volume and 69.98 gm in weight each] per batch, 25 kg of material for each batch was prepared and moulded into jerry-cans using the machine (Photograph 3.2).

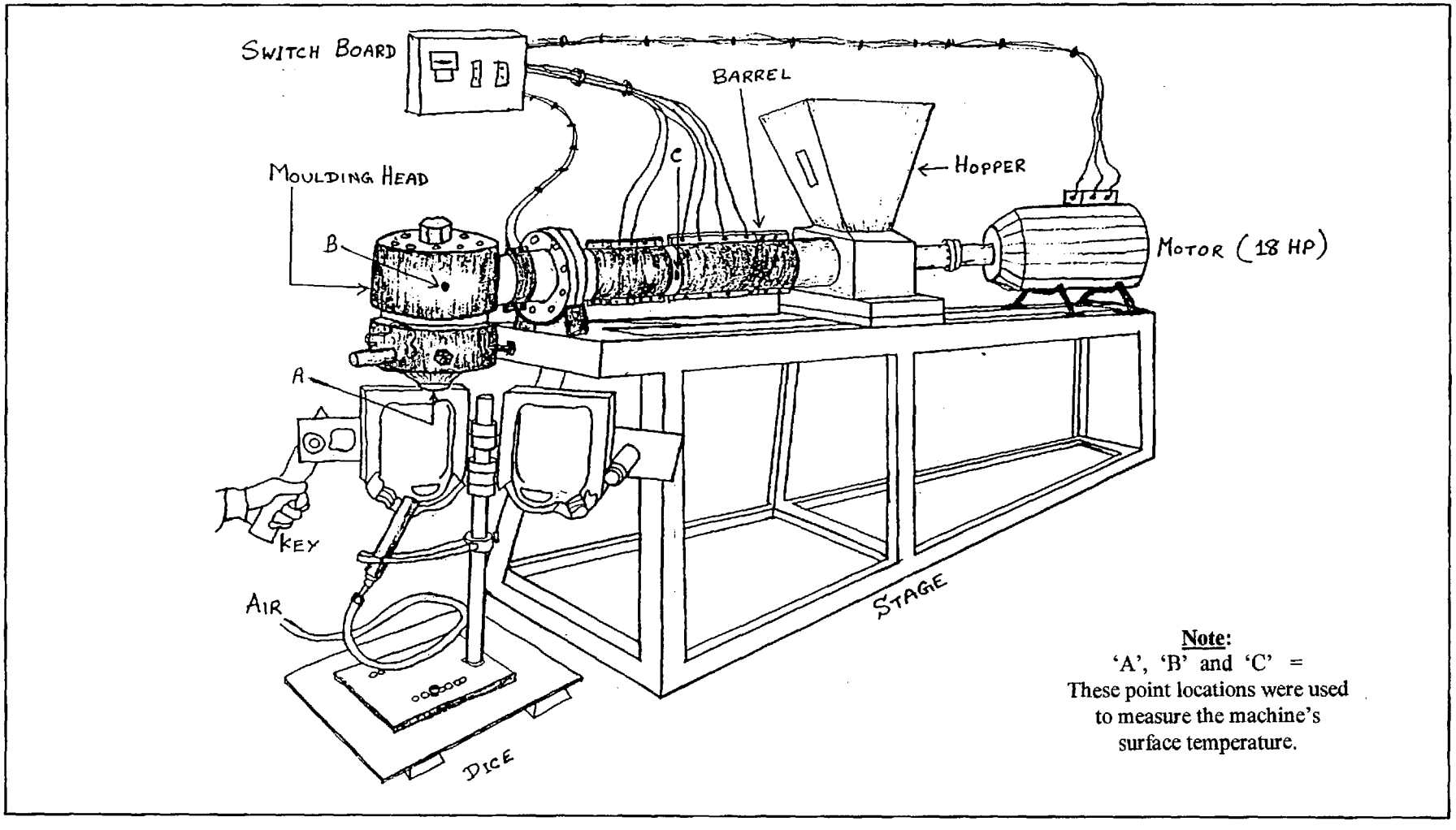
3.4.3 Purging of the Machines

Before starting moulding, two deep blue coloured 'master batch pellets' were put into the hopper of the machine and then about 2 kg of virgin pellets were fed. The machine was then started and observe its motion of how many jerry-cans were required to be discarded to run out all the blue colour effects of the master batch. Based on the findings from this attempt, it was decided that, before starting sample collection, purging the machine must be carried out by discarding the first 20 products. The same die and same moulding and shredding machines were used for all the total of 51 in-house reprocessing trials. All these semi-mechanised machines were manually operated and controlled. In particular, the heat supply to the moulding machine's barrel was controlled just on the basis of experience of the operator involved. Sufficient precautions were also made before using new batch of feedstock for pelletising, granulating and moulding, in order to prevent possibilities of cross contamination. Similar methods were also followed for purging both the shredding and pelletising machines where the first 3 kg of flakes and pellets were discarded, respectively. Cleaning up these machines was also performed manually when and where required. Sometimes cleaning of filters or replacing them with new ones in the head of pelletising, agglomerating and moulding machines was carried out.

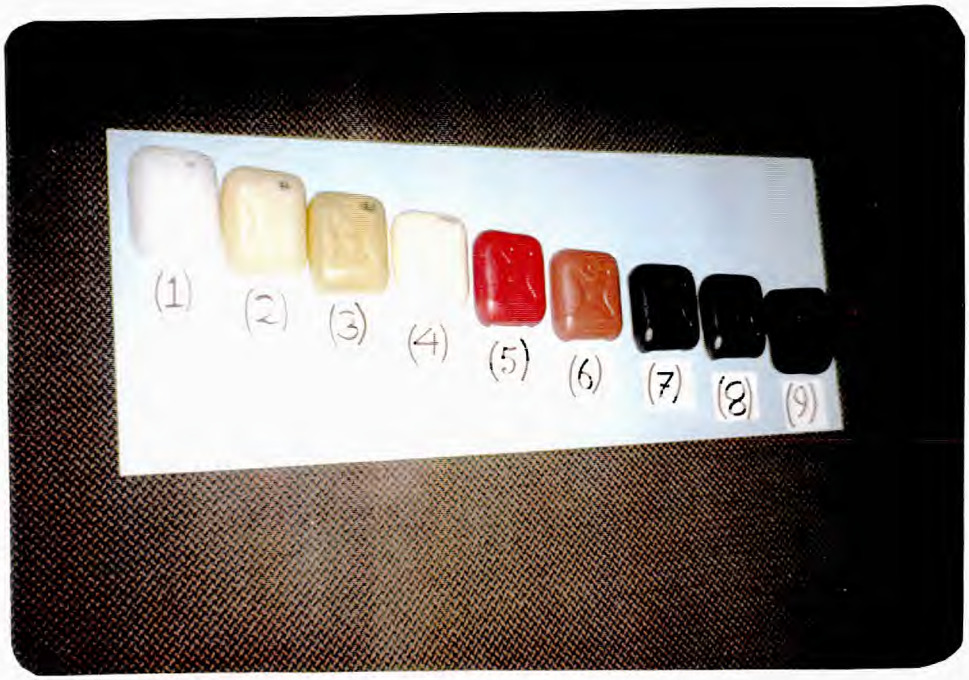
3.4.4 Successive Moulding and Sample Jerry-cans Collection

In-house successive extrusion-blow-moulding was initiated by extruding the 10 kg of virgin HDPE (denoted as Pro-0). A total of more than 140 nos. jerry cans were produced and every 11th product was collected as a sample to give 12 replicate samples. Remaining 108 nos. of jerry-cans were shredded into flakes to give feedstocks straightaway for the next in-house moulding. It means that these shredded flakes missed the chance

Figure 3.5: A commonly used and locally made Single-screw Extrusion-blow-moulding Machine, Dhaka.



Photograph 3.2: Sample jerry-cans moulded from nine different batches of feedstocks as shown in the Photograph 3.1.



Photograph 3.3: Translucent virgin pellets successively moulded using a single screw extrusion blow moulding machine in Dhaka [Pro-1 on the left to Pro-7 on the right].



becoming contaminated whilst passing through the process of 'consumption-disposal' stages of each of the recycling loops. However, the same procedure of moulding the shredded feedstocks into jerry-cans was succeeded by collection of samples, shredding the remaining products, and then moulding the flakes again into products. Following this procedure, the virgin pellets were successively reprocessed up to seven times (Table 3.6 and Photograph 3.3).

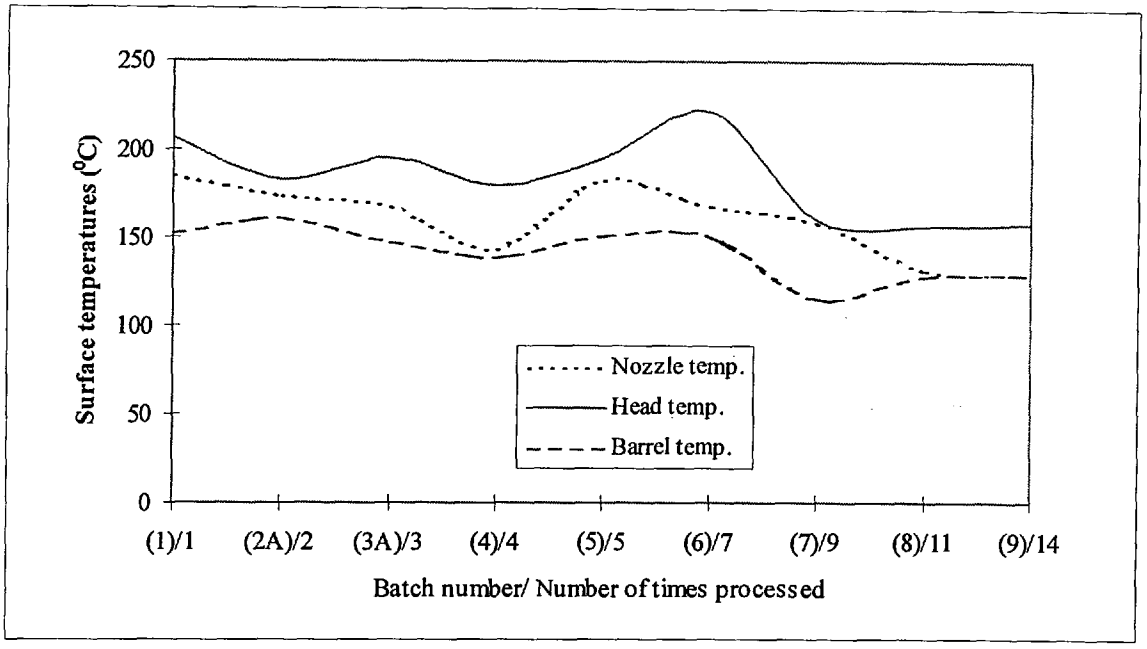
Exactly the same procedure of successive extrusions and sample collections were followed in the cases of the other 11 categories of sample feedstocks made of HDPE general scraps. The same moulding and shredding machines were used in all of the cases. Different batches of the scraps were reprocessed successively for a different number of times (Table 3.6), depending on a number of local factors during the field study in Dhaka, viz. availability of the moulding machine used, time, and resources.

Finally, a total of 51 different batches of sample jerry-cans were collected (Table 3.6). Collection of 12 replicate samples for each of the 51 different reprocessing trials gave 51 x 12 = 612 nos. sample jerry-cans. Back-middle portions of these jerry-cans were cut off and used subsequently as test specimens in laboratory experiments to determine their properties (in Chapter 5).

3.4.5 Measuring Moulding Condition: Machine's Surface Temperatures

The machine was pre-heated for two hours before starting moulding. Since no temperature control unit was attached to the machine used in Dhaka city, its surface temperature was measured at three different points: nozzle, barrel head and middle of the barrel (Figure 3.5). Temperature was measured using a thermocouple surface probe (K-type) connected to a Whitman DT 100 thermocouple thermometer (K-type). The nozzle temperatures ranged from 180 ^{0}C for the virgin material to 130 ^{0}C for the material previously processed 13 times. Accordingly, the ranges of temperatures measured for the other two points were 191-158 ^{0}C and 157-129 ^{0}C, respectively. These were the best possible estimates of the materials' melt temperatures. It was observed that a lower temperature was required for the material processed a higher number of times (Figure 3.6 and Appendix 3.1).

Figure 3.6: Surface temperatures of the moulding machine measured at three different points during successive in-house reprocessing, Dhaka.



3.5 Production Cost of Sample Jerry-cans

In order to determine factory prices of successively recycled jerry-cans, according to their deteriorating quality, actual costs of all input variables which make up factory prices were measured on the basis of the information obtained from direct observation during the moulding of the sample jerry-cans (Table 3.7). For comparison, sample jerry-cans were also placed in front of 30 moulding machine operators to determine their factory prices according to their apparent /visible condition/quality. Nothing was mentioned in advance to the operators about how many times a particular sample product had been reprocessed. These operators were experienced in understanding the quality of recycled products on the basis of their visual observation, feeling and smelling, and thus quite efficient in determining their prices accordingly.

3.6 Sample Collection and Transport to London

The following items were brought back into the UK for laboratory analysis (Table 3.8).

Table 3.7: Estimated market prices of HDPE jerry-cans (2 litre) according to their number of times processed in Dhaka. [US$ 1.00 ≈ Taka 41.50 (April, 1996)].

Description of the feedstocks used, by their No. of times Pro. & Rcy.	Unit price of materials (Taka/Kg)	Production cost per piece of 2 litre jerry-cans (In Taka ⇒ TK.)				Manufac-turer's profit margin	**Factory price per piece of jerry-cans[2]**	
		Material	Machine operator	Power energy	Purging machine[3]		In Taka[4]	In US$[5]
Pro. - 0 Rcy.- 0	66.14	4.62	0.35	0.68	0.60	1.75	8.00 *8.70* (8.00)	0.19
Pro.- 1 Rcy.- 0	50.71	3.55	0.35	0.68	---	1.50	6.08 *6.35*	0.15
Pro.- 2 Rcy.- 0	41.89	2.93	0.35	0.68	---	1.25	5.21 *5.15*	0.13
Pro.- 3 Rcy.- 0	35.27	2.47	0.35	0.68	---	1.00	4.50 *3.80*	0.11
Pro.-4/5 Rcy.- 1	30.86	2.16	0.35	0.68	---	1.00	4.19 *4.10* (4.00)	0.10
Pro.-6/7 Rcy.- 2	24.25	1.70	0.35	0.68	---	1.00	3.73 *4.00*	0.09
Pro.-8/9 Rcy.- 3	19.84	1.39	0.35	0.68	---	0.70	3.12 *3.05* (3.00)	0.08
Pro.-10/11 Rcy.- 4	17.64	1.24	0.35	0.68	---	0.50	2.77 *2.75*	0.07

Note: [1] For explanation of the notations, please see explanations under the Table 3.6.

[2] Factory prices based on: Unit price of electricity = TK. 3.50 (including maintenance cost); Actual rate of electricity = TK. 3.00 /unit (220V) and TK. 2.60/unit (440V). Electricity required per production of a 2 litre jerry-can = 0.1943 unit.

[3] "---" Cost covered by operator's charge, because purging of moulding machine is not carried out frequently in Dhaka, although some times cleaning of filter or replacing it in the head of moulding machine is required.

[4] Factory prices obtained from direct observation and interviewing informally are shown in normal and italic fonts, respectively. Prices within the bracket are existing factory prices.

[5] US$ 1.00 ≈ Taka 41.50 (April, 1996).

Table 3.8: List of HDPE materials brought back into the UK from Bangladesh and India.

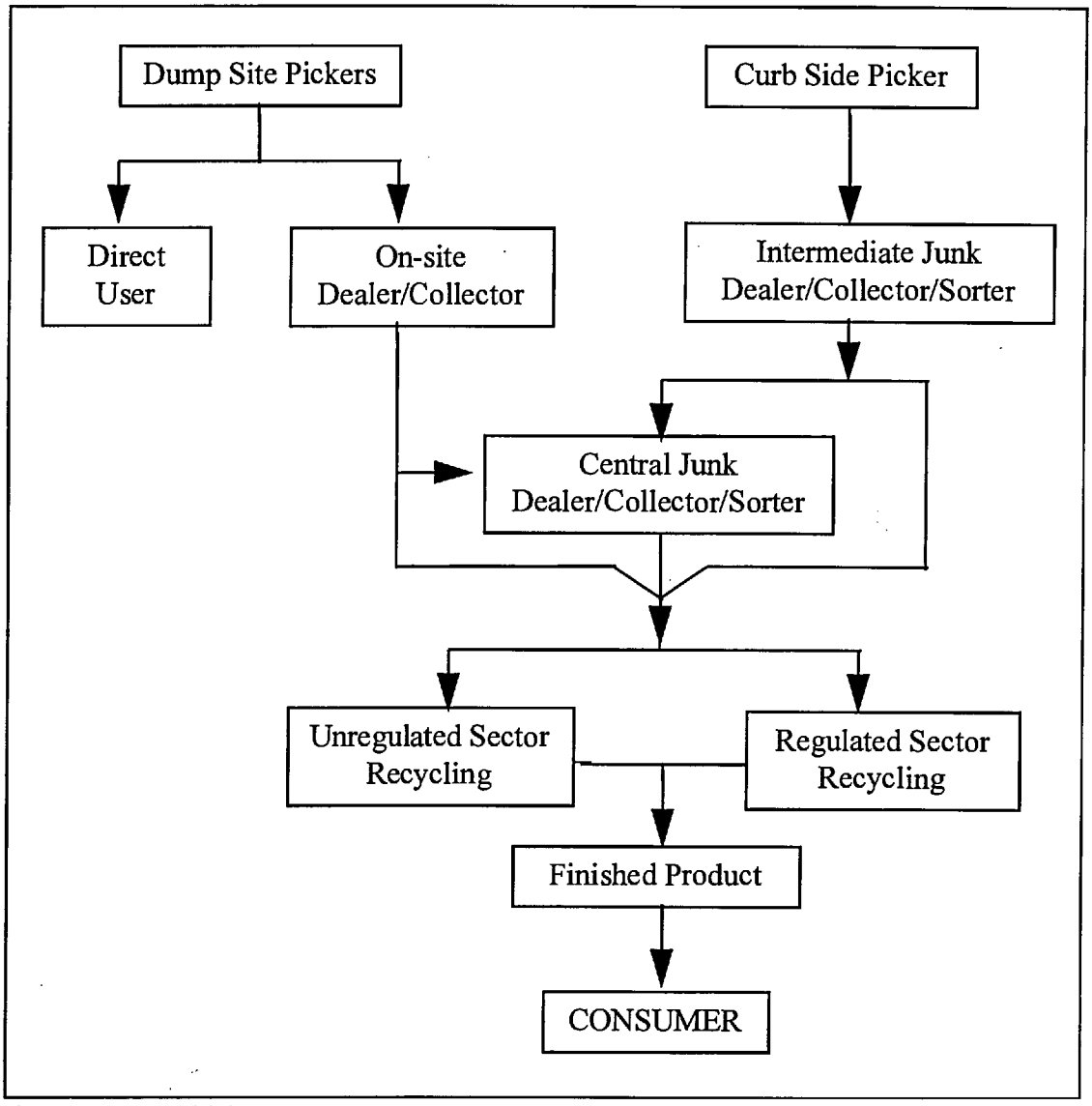
Descriptions of Items	Quantity Required
From Bangladesh	
Replicate sample jerry-cans (back middle part only) from 51 batches of sample jerry-cans produced in **Dhaka**	51x12 = 612 nos.
Translucent virgin (rounded) pellets: **(1)/0**	5 Kg
Translucent flakes (of short life /large/ whole /single type of waste articles): **(2A)/1**	5 Kg
Translucent flakes (of long life /large/ whole /single type of waste articles): **(2B)/1**	5 Kg
Pellets (of short & long life translucent discarded articles & fractions): **(3A)/2**	5 Kg
Same batch of [3A/3] but washed twice & colour flakes removed before pelletising: **(3B)/2**	5 Kg
Same batch of [3A/3] but chaff won before pelletising: /(3C)/2	5 Kg
Milky coloured pellets **(4)/3**	5 Kg
Granules of brown coloured wastes: **(5)/4**	5 Kg
Granules of dull-brown coloured waste: **(6)/6**	5 Kg
Granules of black coloured waste: **(7)/8**	5 Kg
Granules of dull-black coloured waste: **(8)/10**	5 Kg
Granules of very dull-black coloured waste: **(9)/13**	5 Kg
From India	
Replicate sample jerry-cans of 03 different batches of white, blue and black moulded from the feedstock collected from the **Calcutta** plastics market	3 x 12 = 36 nos.
Replicate sample jerry-cans of 03 different batches of white, blue and black moulded from the feedstocks collected from the **Delhi** plastics market	3 x 12 = 36 nos.

3.7 Case Study in India: Calcutta and Delhi

A similar approach was followed, as in the case of fieldwork in Dhaka, during the field research in Calcutta and Delhi for literature searching, meetings with appropriate persons and interviewing them informally. Some descriptive literature on plastic recycling in Indian cities was also obtained. In general, plastics recycling systems in the Indian metropolises are very similar to the system operating in Dhaka, but the Indian system is more specialised and one step forward technologically and conceptually for recycling most plastic types. The Indian system is well equipped. In many cases, it involves large industrial establishments compared to small units in Dhaka. In addition to these contrasts, the Dhaka plastic recycling system is entirely operating under an unregulated sector (Figure 2.1 in Chapter 2), whereas the Indian cities (e.g. the Calcutta plastics recycling

system) are based on two parallel recycling sectors - unregulated and regulated as shown in Figure 3.7.

Figure 3.7: Plastic wastes recovery-recycling system of Calcutta.



Source: EIP, 1996.

Moreover, contrary to the centralised distribution pattern of plastic recycling units in Dhaka city (as already shown in Figure 2.2 in Chapter 2), recycling units in Calcutta and Delhi are developed into a clustered pattern across the city area (Figures 3.8 and 3.9). However, under the pressure of similar socio-economic forces as in Dhaka city (sub-section 2.2.1 in Chapter 2), a single directional flow of plastic waste has also been operating for Calcutta and Delhi city with a large catchment area for more than a quarter of a century. For example, plastic wastes generated in the three neighbouring Indian states of West Bengal, Orissa and Bihar are transported to Calcutta city and

recycled along with the imported plastics in many areas of the city, mainly at *Tangra* and *Topshia* located on the west bank of *Dhapa*[1], *Narketdanga, Cannel South Road, Taliganj, Maniktala, Shobhabazar, Bali,* and *Haora* (Figure 3.8). Similarly, Delhi also offers a number of areas for recycling huge amounts of plastic waste brought from all of the surrounding provinces and abroad. The areas with a higher propensity of the plastics recycling activities are: *Jawalapuri*[2], *Mangolpuri, Udyog Nagar, Piragarhi, Trinagar, Wazirpur,* and *Kirti Nagar* in the north-western part of the city; and *Malka Ganj, Sadar Bazar, Vishwas Nagar* and *Balbir Nagar* in the north-eastern part; and *Ansari Nagar, Alaknanda, Amar Colony, Sriniwaspuri, Cambridge School, New Okhla Industrial Estate,* and *Small Industries Bhavan* in the south-eastern Delhi - New Delhi (Figure 3.9).

During the research it became apparent that a useful survey report on "Life Cycle Analysis of Plastic Waste in Indian Metropolises: Ahmedabad, Bombay, Calcutta and Delhi" was being produced, which was due to be published by the beginning of 1997 (Bashu, 1996). However, according to the latest information received by the end of November 1997, the report has not been published yet due to some administrative reason (Bashu, 1997).

A close look at a plastic community - *Tangra*, Calcutta:

Ganguli (1995) reported that the total number of plastic factories in Calcutta as estimated by the Directorate of Factories, Government of West Bengal was about 1000. He added that the actual number of plastic factories operating far exceeded the number presented here which represented only a small portion of the factories (30 % of the total number) registered under the Factories Act 1948. However, the results obtained from the fieldwork in the

[1] *Dhapa* used to be the huge marshy land in the eastern fringe of Calcutta city which has been used as a disposal site of the city's waste products since the early days of this century (Source: Kundu, 1985; EIP, 1996).

[2] *Jawalapuri* used to be Asia's largest recycled plastic market but it has now been evacuated following a fire incident in late 1995 (Source: Fieldwork, 1996).

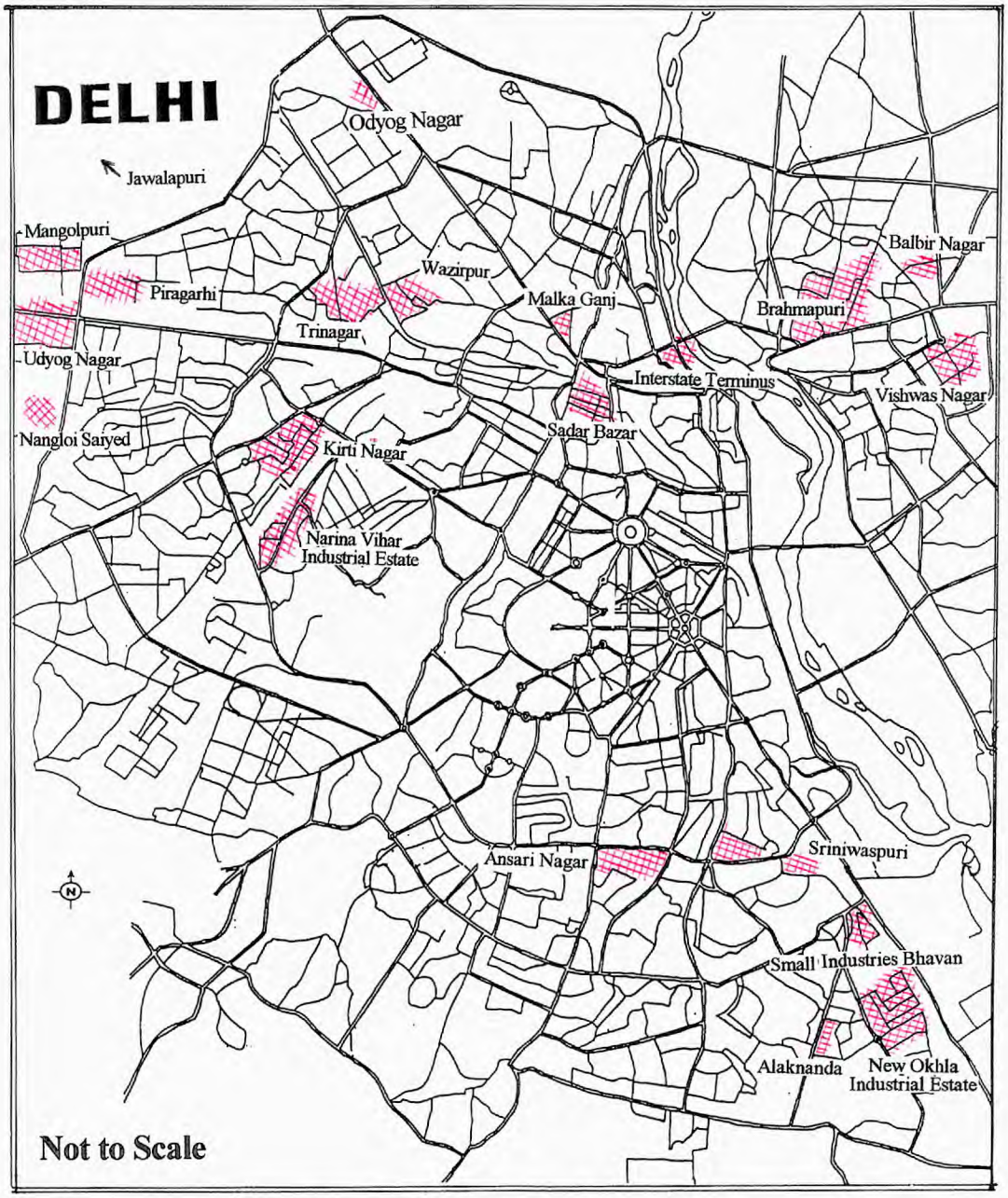
Figures 3.8: Plastics recycling activity areas in Calcutta, 1996.



Data Source: Questionnaire survey and field investigation, 1996.

Map Source: Poovendran, 1995a.

Figures 3.9: Plastics recycling activity areas in Delhi, 1996



Data Source: Questionnaire survey and field investigation, 1996.

Map Source: Poovendran, 1995b.

Tangra area (Figure 3.8), under the Calcutta Municipal Corporation Ward No. 57, have revealed following facts:

The people residing in this area were of two broad categories - middlemen or wholesalers and recycling unit operators. The wholesalers collect the plastic waste from Calcutta and Haora, and some extent from other parts of West Bengal and neighbouring

provinces, e.g. Orissa, Bihar. Plastic waste traders sort out different types of plastics by their colour and composition categories, depending on their experience. As in the case of Islambagh in Dhaka, almost every member of the family in this area takes part in this operation. After initial sorting out of the plastics, they are shredded into flakes and then washed with detergents and kept in the open sun light for drying. Washed and dry flakes are then passed for pelletising / agglomerated mostly within Tangra area. It is generally believed by the recyclers that 20 - 30 thousand workers are engaged in these activities in the Tangra area alone. According their opinion, a total of roughly 20 thousand plastics recycling factories are present and in operation in Calcutta.

- The recycling units may also be divided into two categories - units with higher capital investment (Photograph 3.4) and units with lower capital investment (Photograph 3.5). The wholesalers directly sell the sorted plastic waste to the former. The latter units operate on a commission basis and only process the waste into pellets. The majority of the recycling units (80 %) which have appeared in the last decade are in this category. The rest form different consumer products from these pellets. These units remain in operation for the whole day long, with two shifts of 12 hours stretch.

- Almost similar moulding machines as in Dhaka but attached with a temperature control unit and more effective electrical fittings are in use in Calcutta and Delhi cities for recycling HDPE.

- Since these recycling units are capital intensive, the numbers of labour employed is less than ten. This number varies with the size of the operation of a unit. It agrees with the observation of Ganguli (1995) that, along with men and women labour, a large number of factories were seen to be having child labour under fourteen years of age, thus openly flouting The Child Labour (Prohibition and Regulation) Act 1986. There is a discrimination in male and female wages. The temporary labours work on 'no work no payment' basis.

- The in-door environment of these recycling units can generally termed as very filthy. The workers suffer from a thermal stress. The exhaust ventilation is inadequate, even when they are present they remain in operational. Most of the recycling units, in order to hide from the Government authorities, have closed or sealed up all the windows,

Photograph 3.4: Plastics recycling units with higher capital investment, *Tangra*, Calcutta.



Photograph 3.5: Plastics recycling units with lower capital investment, *Tangra*, Calcutta.



which thus adds to the state of degradation of the workers' environment. Ganguli (1995) reported that asthma is prevalent among the aged persons of the community, and there are sporadic cases of dermatitis and other skin diseases which may be attributed to the exposure to toxic gases and vapour emitted during thermal degradation of plastics.

Sample feedstocks collection from Calcutta and Delhi:

According to the basis used in sample feedstocks collection in Dhaka, 3 different batches of HDPE general scrap granules of 3 different colours (i.e. translucent, blue and black) were collected from both the Calcutta and Delhi plastics markets. All these 6 batches (3 x 2) of granules were then transported to Dhaka, and moulded into 2 litre jerry-cans using the same extrusion-blow-moulding machine (Figure 3.5) used in the case of the Dhaka materials. Sample jerry-cans were collected and test specimens were cut off from their back-middle portions. Subsequently, their properties were determined in London along with the Dhaka specimens. A comparative analysis between the properties of the specimens collected from the three cities is performed in Chapter 5.

CHAPTER 4:

Effects of Successive Reprocessings on the Properties of HDPE Processed in London

4.1 Introduction

Reprocessing a plastics material may affect its properties either in a positive or negative direction depending on a number of known and unknown factors involved. Any change, in any direction in the original properties of the plastic due to reprocessing is a sign of degradation. The factors responsible for a change could be associated either with: the original properties (mechanical, thermal and chemical) of the plastic with which reprocessing started, the processing conditions and consistency, how well the test materials and equipment were looked after, the level of systematic and experimental errors, or, the combined effects from all or some of these factors. These facts imply that an attempt at assessing the effects of successive reprocessing on polymer properties is a tough and difficult business, particularly for one from a non-polymer science background.

Therefore, this Chapter is designed primarily to explain critically the initiatives undertaken and to procure an overall understanding on how a known grade (*Marlex*, Grade No. HHM 5502-0304, Batch No. MI 2819) of virgin High Density Polyethylene (HDPE) behaves whilst it has been successively reprocessed up to 15 times under in-house environment and known processing conditions at the School of Polymer Technology, University of North London. Thus, with the knowledge derived from this Chapter, it would be easier in the next Chapter 4 to perform experiments with a number of unknown grades of HDPE recycled several times in Bangladesh and India. Plastic recyclers in these countries process their materials under unknown processing conditions using locally produced manually operated recycling machines. They perform their jobs depending entirely on their life long experience and skill gathered progressively.

Following experimental details, results obtained from the laboratory tests are explained below under a separate sub-section for each of the properties investigated. Analysis and discussion of the results are also made subsequently within the same sub-section of the results.

4.2 Experimental Details

4.2.1 Materials

The polymer material used in this study is High Density Polyethylene (HDPE) resin (rounded pellets) manufactured by Phillips Petroleum Singapore Chemicals (Private) Limited, Republic of Singapore, under the trade name *Marlex*, Grade No. HHM 5502-0304, Batch No. MI 2819. The reason for using this resin is that it is being imported and used in Bangladesh to produce new plastic articles which will eventually enter into the country's plastics recycling stream.

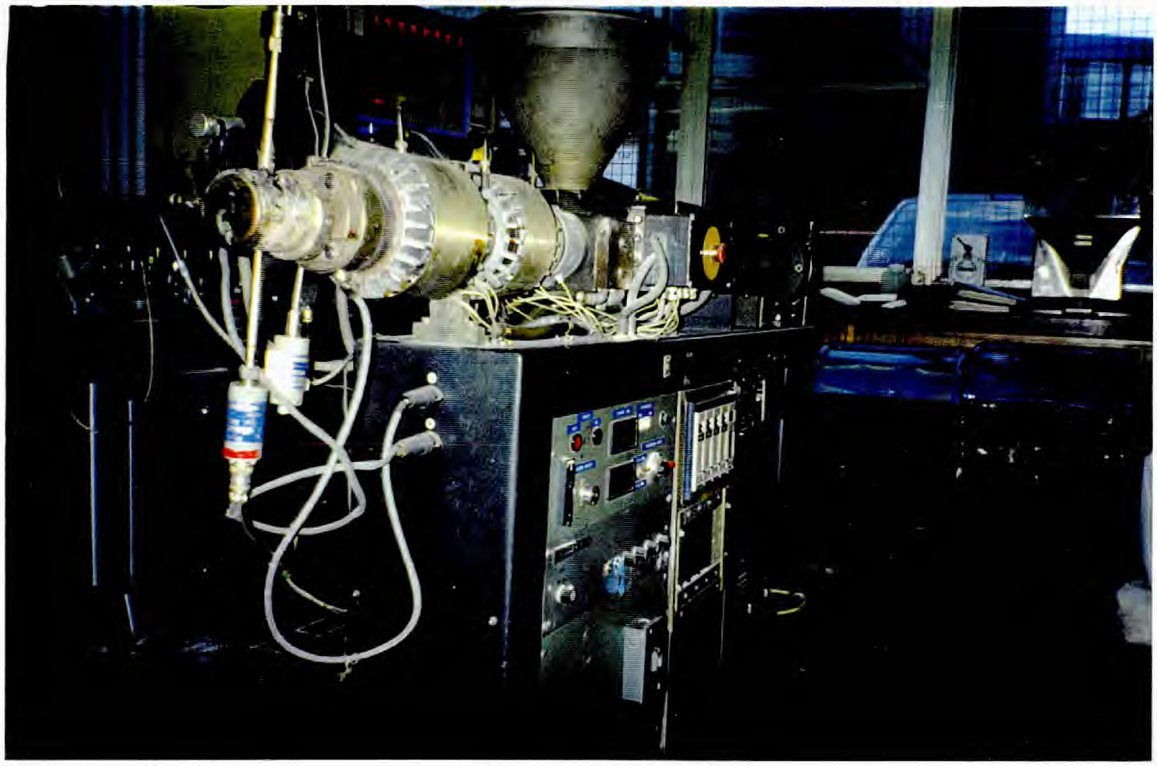
4.2.2 Extruding, Pelletising and Sample Collection

In-house successive extrusions up to 15 times were initiated, starting with extruding 5 kg of the virgin HDPE pellets. This material is defined in this study as Pro-0 which means that the material has not previously been processed. All 15 extrusions were performed using a Brabender 330 twin screw extruder fitted with a die of diameter 4 mm and length 16 mm (Photograph 4.1). The machine was pre-heated for two hours before extruding started. The melt temperature was 197-198 ^{0}C and the screw speed was 4-5 rpm. The range of temperature readings displayed on the extruder for the back/middle/middle/front zones of its barrel are 163-168/199-200/200-201/199-200 ^{0}C against their corresponding temperatures set at 190/200/200/200 ^{0}C. The extrudate was then passed through water to cool it and pelletised into 3 mm x 4 mm "rod pellets".

Since the material was extruded using a *twin screw* extruder set with a *low screw speed* (4-5 rpm) and a *short retention time* (2-3 min) , no significant 'shearing effects' were experienced by the materials. In a twin screw extruder materials are moved forward freely, whereas a single screw extruder shears materials by compressing and chafing them with the inner walls of its barrel.

At the middle of the extrusion, a sample of about 45 g melted extrudate (estimated by 1¼ minutes collection) was collected and coiled as tightly as possible on a galvanised aluminium plate (Photograph 4.2) and taken immediately to a pre-arranged presser for

Photograph 4.1: Brabender 330 twin screw extruder.



Photograph 4.2: Melted and tightly coiled HDPE extrudate on a galvanised aluminium plate.



sheet making, according to the procedure described in the following sub-section, for tensile strength tests. At the end of the extrusion, 100 g of once processed pellets were collected at once as a sample into a bag labelled with 'Pro-1' for measuring rheological properties. After sample collection, the rest of the once processed pellets were put back straightaway into the hopper of the extruder for the next processing. All of the steps as mentioned above were repeated under the same extruding conditions within three consecutive days by maximising and maintaining consistency as much as possible, in order to get another 14 different batch of pellets processed from twice to 15 times. In total 16 different batches of pellets and the same number of batches of sheets, including one sheet made of the virgin plastic were collected and labelled as Pro-0, Pro-1, Pro-2, ... Pro-15 for testing. All possible efforts were made to purge the extruder and pelletiser before starting each successive processing. Careful observation was also undertaken to avoid any possibility of cross contamination.

4.2.3 Pressing Melted Samples into Sheets

A two Speed Hydra-Pak Hand Pump presser (750-4500 PSI; Sl. No.: 6828) fitted with two vertically adjustable platens (10 cm thick) designed for heating up and cooling down (Photograph 4.3), was used to press the melted coiled sample into a 1.57 x 15 x 15 mm sheet. By keeping the cool water supply off into the platens, both of the platens were pre-heated with the temperature set at 200 ^{0}C by switching on a heater. These platens were set apart to leave enough space for placing melted coiled sample on a square aluminium plate surrounded with a die frame of 1.57 mm thick and covered by another plate (Photograph 4.3). The coiled sample was placed in a hot condition without any delay after collection. As soon as the sample was positioned properly, both the heated platens were brought together to close the gap and thus to touch and press lightly the plates. At this stage, a one minute interval followed to allow the sample to melt properly and be redistributed over the die space enclosed by the plates and die frame.

After this interval the platens were locked at first and then pressure was built up to 20.32 tonnes (20 UK tons) on the platens to drain out spaces between the die frame, plates and platens. As the sheet settled down, the ram pressure also came down. Thus increasing ram pressure again up to 20.32 tonnes was performed 2-3 times until the pressure reader

Photograph 4.3: Coiled sample surrounded with a die frame and plates placed between the platens of a two speed Hydra-Pak Hand Pump presser.



Photograph 4.4: Dumb-bell specimens prepared from successively processed material: (a) the extrusion-blow-moulded jerry-cans made of HDPE general scraps, (b) the extrusion-blow-moulded jerry-cans made of the virgin HDPE, and (c) the sheets pressed off the coiled extrudate made of the virgin HDPE.



needle became stable around 18/19 tonnes, in order to produce a sheet of 1.57 mm thick by squeezing out all air bubbles from the sample. The heater was then switched off and the platens were cooled down sufficiently by switching on a cool water supply. Platens locked in position were then released and taken apart. The sheet was collected by opening the plates and then labelled appropriately. Switching off the water supply and switching on the heater to re-heat the platens up to the set temperature ended the first sheet making process and initiated the next processing.

4.2.4 Cutting Dumb-bells from Sheets

Five dumb-bells as replicates were punched from each of the 16 sheets processed different number of times (bottom row in Photograph 4.4). The dimensions of the dumb-bells were: (a) overall length = 75 mm, (b) width of ends = 12.5 $\pm$ 1.0, (c) length of narrow parallel portion = 25 $\pm$ 1.0, and (d) width of narrow parallel portion = 4.0 $\pm$ 0.1. Thickness was measured by a screw micrometer (reading to 0.01 mm or less) at the middle and two ends of the narrow parallel portion of all the dumb-bell specimens and the measurements were recorded for determining tensile strength .

4.2.5 Moulding Plaques

Plaque specimens of dimensions 8.75 x 8.75 x 1.5 mm were injection moulded on a GKN Machinery 15MR injection moulding machine (Photograph 4.5). The machine was pre-heated for two hours before starting moulding. Plaques were produced only from two batches of pellets processed zero times (Pro-0) and 15 times (Pro-15). The processing temperatures were 226/235/238 ^{0}C at three different zones on the machine. Pressure was set at 10 x 10^{5} Nm^{-2} for Pro-0 material and 11 x 10^{5} Nm^{-2} for Pro-15 material to get properly moulded plaques. Plaques were labelled immediately after collection. The machine was purged through before the start of moulding with a new batch of material.

Photograph 4.5: A GKN Machinery (15MR) injection moulding machine.



Photograph 4.6: An Instron 1122 tensile strength testing machine.



4.3 Testing Procedures

4.3.1 Tensile Tests

Five replicate dumb-bell specimens from each of the sixteen different batches of sheets (Pro-0 to Pro-15) were tested in tension on an Instron 1122 tensile strength testing machine (Photograph 4.6) at a cross head speed of 100 mm per min, a full scale deflection of 200 N and a chart speed of 100 mm per min. The computer programme connected to the Instron -Series IX Automated Materials Testing System, Version 5.33, 1995, Instron Corporation - was used to measure different parameters of tensile strength. The British Standard Test Method 320A: 1976 was followed (BSI, 1997a). Before using the machine, calibration was carried out at the start of testing with new batch of dumb-bell specimens and also in the middle of testing, when necessary. The quantities of the parameters measured from the recorded load-displacement diagrams for the specimens were: (i) the stress at yield calculated on the basis of the maximum load required to initiate deformation or elongation, (ii) the stress at break calculated on the basis of the maximum load required to break the specimens at the maximum elongation point, (iii) the strain (deformed length over original length) at yield, and (iv) the strain at break.

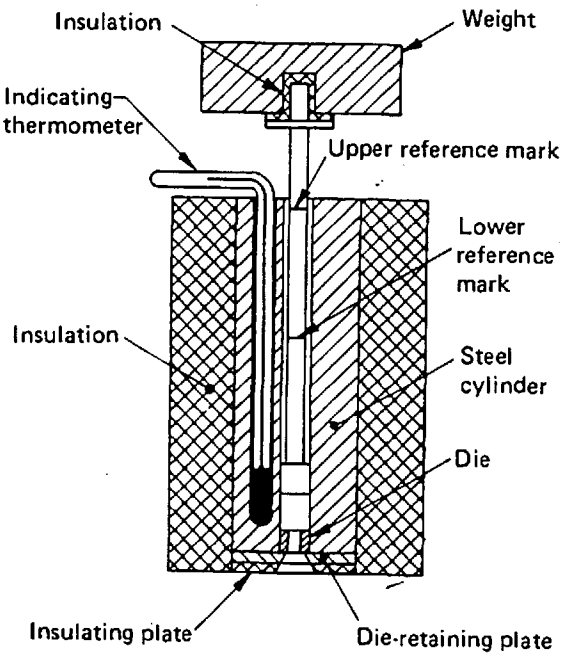
4.3.2 Melt Flow Rate Test

Melt flow rate (MFR) tests of sixteen different batches of pellets (Pro-0 to Pro-15) were performed using a Davenport Sl. No.: 851 MFR tester (Photograph 4.7) fitted with a piston in a cylinder bore fitted with a die of diameter 2.09 mm and length 8 mm. The British Standard Test Method 720A: 1979 was followed (BSI, 1997b). The materials under test were in pellet form. Before starting the test procedure, the equipment was pre-heated for an hour with a barrel temperature set at 190^0C.

Before each determination, the die and mechanical piston were removed (Figure 4.1). The working surfaces of the piston and cylinder bore were cleaned, while still hot, by means of cloth patches supported on a loose-fitting non-abrasive rod. The die was cleaned with a non-abrasive auger and replaced in position. Purging the cylinder bore

and die with the material under test, before each of the sixteen trials, was preceded by charging the cylinder. Then the cylinder, with appropriate die and piston in position, was maintained at the selected temperature for a period of 15 minutes. The piston was removed and stored in the piston sheath. The cylinder was then charged again with an amount of material of 20-50 mm above the upper face of the die. During charging, the material was compressed using manual pressure on the packing rod, to remove as much air as possible and to ensure uniform heating of the charge. Immediately after charging was completed, the unloaded piston was replaced on top of the charged material, and a stop watch was switched on.

Figure 4.1: Typical apparatus for determining MFR.



Source: BSI, 1997b.

Photograph 4.7: A Davenport (Sl. No.: 851) MFR test equipment.



After 5 min, during which period the temperature of the cylinder returned to the selected temperature after any deviation due to the cooling effect of the charge, a load of 10 kg was placed swiftly and smoothly on the piston to apply the required nominal force. Observation was made during the period the material was being extruded from the die, when the level of the material was less than 50 mm from the upper face of the die (i.e. the lower reference mark on the mechanical piston was no longer visible above the cylinder as shown in the Figure 4.1). As soon as this condition was satisfied, the existing extrudate was cut cleanly off from the die and discarded. A short length of extrudate was cut cleanly at the die and actual time required by that extrudate to extrude, referred

to as "cut-off time", was observed on a stop watch and noted. Then, without any delay, all three jobs of stopping the watch, cutting off the existing extrudate and switching on the watch to measure cut-off time for the next cut-off were performed in rapid succession. A total of three short lengths (less than 3 cm) of cut-offs were obtained for each batch of the material by cutting subsequent extrudate after successive approximately equal intervals of time. Cut-offs were retained in sequence with their corresponding actual cut-off times (within the range of 30 to 38 s) measured on a stop watch, and then, weighed individually to the nearest milligram using a Sartorius Basic, BA160P, electronic weigh scale (Photograph 4.8) giving reading up to four decimal points of a gram. The masses in cut-offs were noted according to their sequence.

No cut-offs were taken when the level of the material was less than 20 mm from the upper face of the die (i.e. when the upper mark of the piston was level with the top of the cylinder). Any cut-offs containing visible air bubbles or not cut cleanly were discarded. The average melt flow rate was determined on the basis of three replicate MFR values calculated from the individual cut-off times and masses using the following formula:

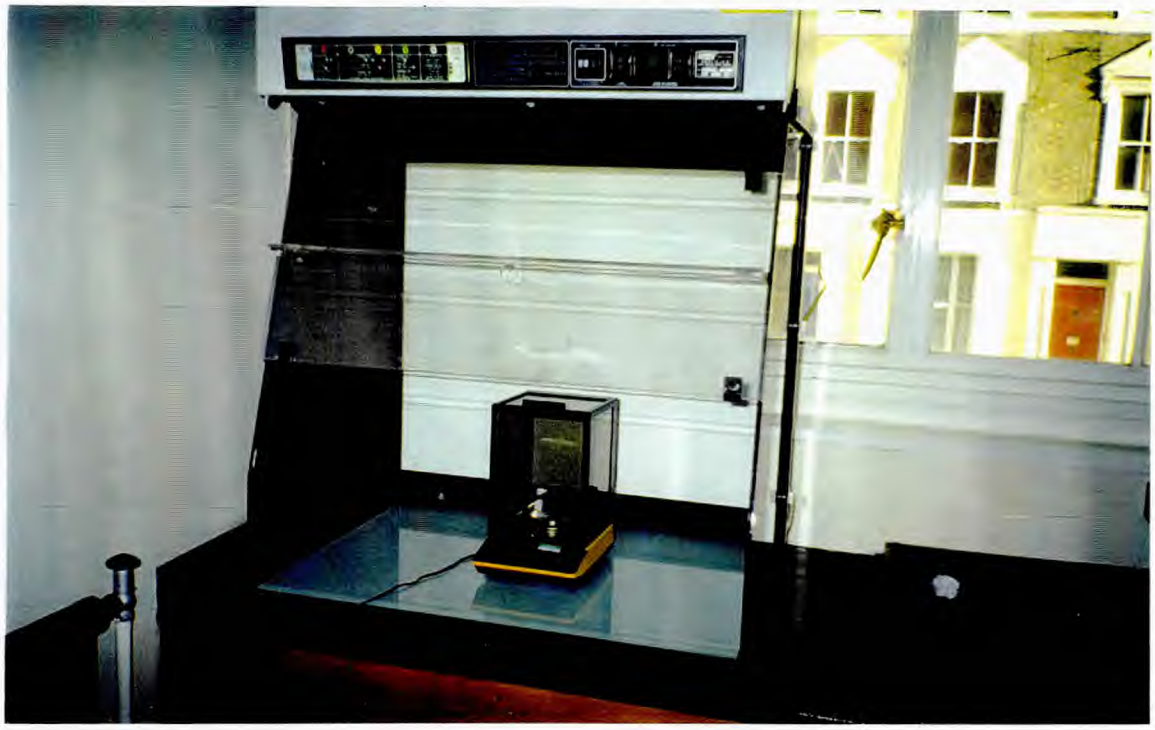
$$\mathbf{MFR}\ (T, F) = \frac{S \times m}{t} \quad (in\ g/10\ min)$$

where, T is the test temperature (190±0.2 ^{0}C),
F is the test force (= 10 kg),
S is the reference time (= 600 s),
m is the mass in a cut-off (in g),
t is the cut-off time (in s).

4.3.3 Viscosity Measurement

Viscosity measurements were performed for two lots of materials - virgin pellets (Pro-0) and the pellets processed fifteen times (Pro-15) on a Davenport Extrusion Rheometer Sl. No: ER 406/11 fitted with a die of diameter 2.5 mm and length 20 mm (Photograph 4.9). The machine was pre-heated for two hours with a temperature set at 190 ^{0}C before starting extrusion. Before each test, the piston and die were removed from the cylinder bore (Figure 4.2). The working surfaces of the piston and cylinder bore

Photograph 4.8: A digital weigh scale - Sartorius Basic, BA160P.

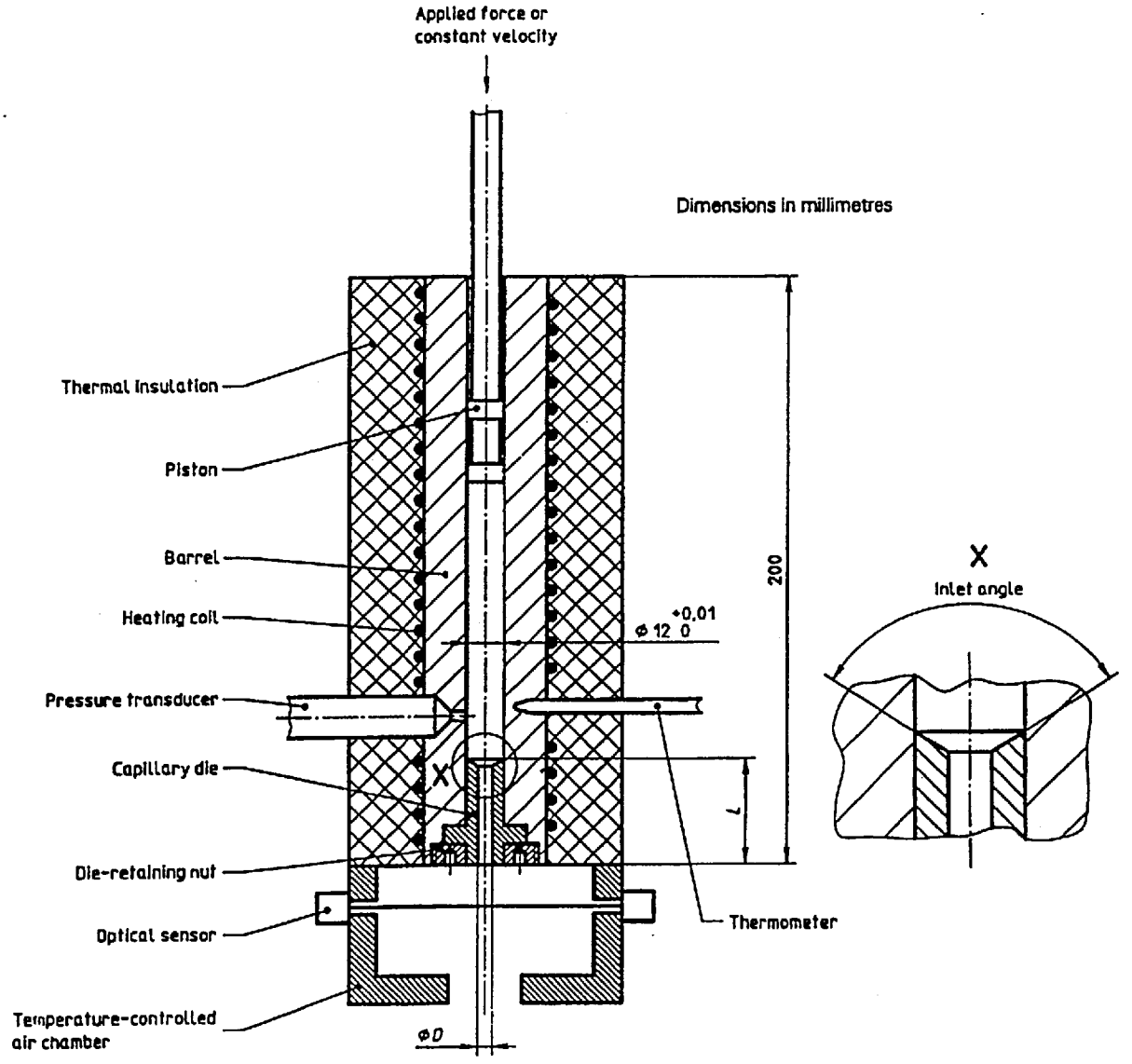


Photograph 4.9: A Davenport Extrusion Rheometer (Sl. No: ER 406/11) used for viscosity test.



were cleaned, while still hot, using cloth patches loosely fitted on a non-abrasive rod. The die was cleaned with a non-abrasive auger and replaced in its own position. After charging the cylinder with the material under test, the piston was fixed into the machine and the cylinder bore and die were purged by switching on the machine to move down the piston for extruding. Then the cylinder, with appropriate die and piston in position, was maintained at the selected temperature for a period of 10 minutes.

Figure 4.2: Typical diagram of an extrusion Rheometer used with a capillary die.



Source: BSI, 1997c.

After that the piston was removed and stored in the piston sheath. The cylinder was charged again with an amount of the material sufficient for evaluation of flow behaviour of the material at different piston speeds. During charging, the material was compressed by moving down the piston mechanically, to remove as much air as possible and to ensure uniform heating of the charge. A period of 10 minutes interval was allowed for the machine to heat up the charge and ultimately the temperature of the cylinder returned to that selected level after the deviation occurred due to the cooling effect of the charge.

Immediately after the completion of all these arrangements, the machine was switched on and pressure readings on a pressure transducer against their corresponding piston speeds were observed and noted down. Pressure readings were examined at both the low speeds of 4, 8, 12 and 16 mm/min and the high speeds of 20, 40, 60 and 80 mm/min. The following formula was used to calculate the viscosity of the materials:

Apparent viscosity, $\eta = \frac{\tau}{\gamma}$ (in Nm^{-2})

where: τ, shear stress = $\frac{Pr}{2l}$ (in Nm^{-2}),

P - pressure (in Nm^{-2})

r - die hole radius (in cm)

l - die hole length (in cm)

γ, shear rate = $\frac{4Q_v}{\pi r^3}$ (in s^{-1}),

Q_v - volume flow rate = $\pi R^2 \upsilon$

R - cylinder bore radius (in cm)

υ - speed (in cm/s)

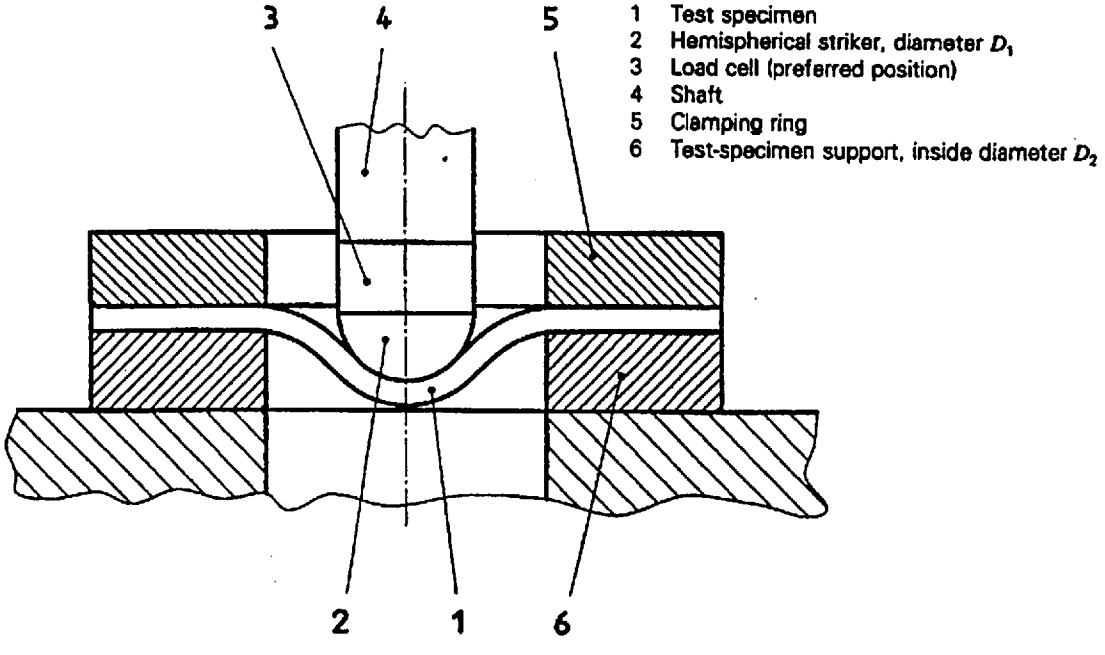
r - die radius (in cm)

It became necessary to undertake flow measurements after determining MFR values. As it had not been originally planned, material was not available for these tests except for Pro-0 and Pro-15. Moreover, it was not possible to repeat the test more than one time to obtain replicate results for the Pro-0 and Pro-15 due to shortage of material. This test was done only for the Pro-0 and Pro-15 materials in order to determine whether these two *first* and *last* materials differed significantly in terms of their viscosity measurements.

4.3.4 Impact Test

The impact strengths of plaque specimens from the Pro-0 and Pro-15 materials only were measured for the same reasons as mentioned in the last paragraph of subsection 4.3.3. After two days of moulding the plaque specimens, the Free-Falling Dart Impact Test were undertaken on a Rosand Precision Instrument Universal Impact Tester (Type 7U) at an impact speed of 3.9 ms^{-1}, sensitivity of 5 kN and filter frequency of 1 kHz (Photograph 4.10 and Figure 4.3). The impact strength results were recorded and analysed using a computer aided programme - Rosand Instrumented Impact Tester, Version V5.12 (12BIT IFW7) - connected to the impact test machine. Impact strengths were assessed in terms of the following impact parameters: (i) force to initiate fracture [in kN], (ii) stiffness (resistance to deformation) factor, (iii) depth of deflection [in mm], (iv) energy required for deflection of fracture [in J], (v) energy required for crack propagation [in J], and (vi) toughness (resistance to crack propagation) assessment factor.

Figure 4.3: Schematic diagram of a impact test apparatus.



Source: BSI, 1997d.

Photograph 4.10: A Rosand Precision Instrument Universal Impact Tester.



4.4 Results and Discussion

4.4.1 Tensile Strength

Table 4.1 summarises the tensile strength test results (Appendix 4.1). There is very little change in the stress at yield across the successive recyclings, which is indicated by the overlapping among the error bars shown in the Figure 4.4. Upper and lower values of each error bar are calculated using the following equations:

$$\text{Mean, } \overline{X} = \frac{\textit{Sum of replicates}}{\text{Number of replicates}} = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$\text{Standard deviation (SD), } \delta = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n - 1}}$$

$$\text{Standard error (SE)} = \frac{\delta}{\sqrt{n}}; \quad \text{Error bar} = \overline{X} \pm \text{SE}$$

Table 4.1 : Summary of the tensile strength test results for the virgin HDPE.

No. of Times Processed	Stress at Yield (MPa)	Strain at Yield (mm/mm)	Stress at Break (MPa)	Strain at Break (mm/mm)
Pro-0	26.9	0.120	24.3	11.07
Pro-1	27.6	0.123	23.9	10.59
Pro-2	26.5	0.117	23.0	10.32
Pro-3	27.4	0.121	25.0	11.51
Pro-4	27.0	0.121	21.5	10.13
Pro-5	27.5	0.118	12.7	6.62
Pro-6	26.7	0.115	11.9	10.06
Pro-7	27.0	0.113	12.4	9.80
Pro-8	27.2	0.119	14.0	7.99
Pro-9	26.4	0.122	13.6	9.60
Pro-10	26.5	0.119	12.1	7.41
Pro-11	27.0	0.114	11.0	8.26
Pro-12	27.0	0.117	11.6	9.02
Pro-13	26.2	0.107	16.4	9.34
Pro-14	27.2	0.118	14.1	7.09
Pro-15	27.6	0.117	15.7	8.88

Figure 4.4 : **Stress at Yield** values of the virgin HDPE after successive processing (±SE).

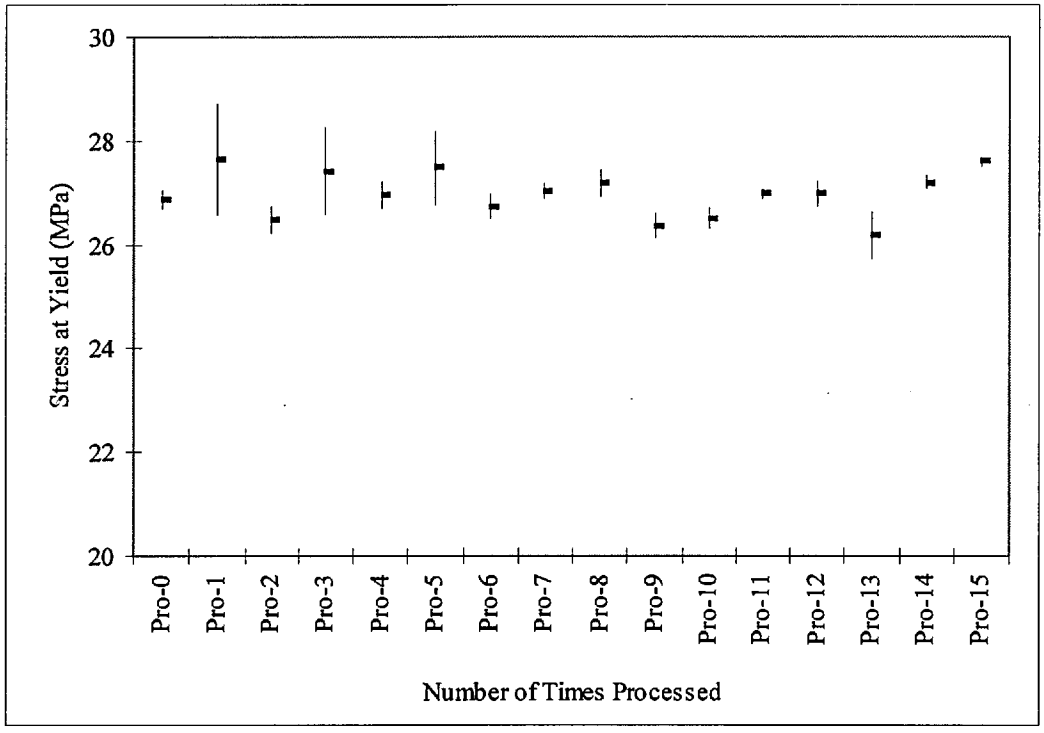
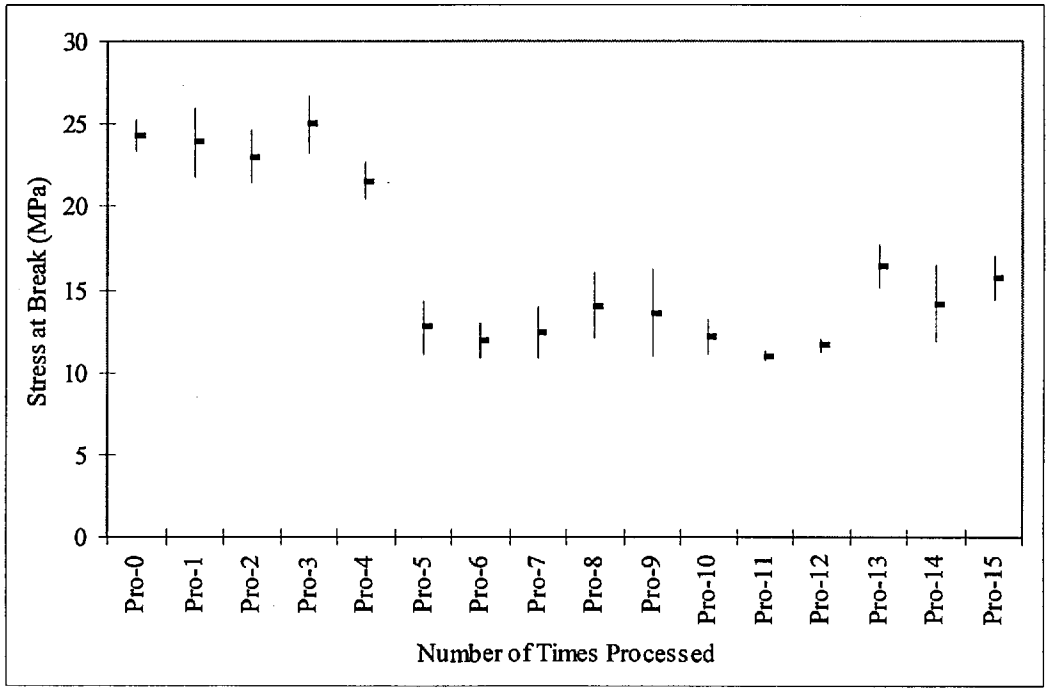


Figure 4.5 : **Stress at Break** values of the virgin HDPE (±SE).



However, there is a *severe* drop from 23.5 to 12.3 MPa in the stress at break around the Pro-4 (Figure 4.5 & Table 4.2). Also there is a *shallow drop* from 10.7 to 8.6 mm/mm in the strain at break around the Pro-4 (Figure 4.6 & Table 4.2). This indicates that the material under investigation behaved differently before and after the 4th time processing (Photograph 4.11). This phenomenon was tested for statistical significance by means of t-tests on the difference between the overall average of stress at break for 'Pro-0 to Pro-4' and that for 'Pro-5 to Pro-15'. Similarly, this test was undertaken for strain at break values. It shows that the differences for stress at break and strain at break are statistically significant (Table 4.2).

Figure 4.6 : **Strain at Break** values of the virgin HDPE (±SE).

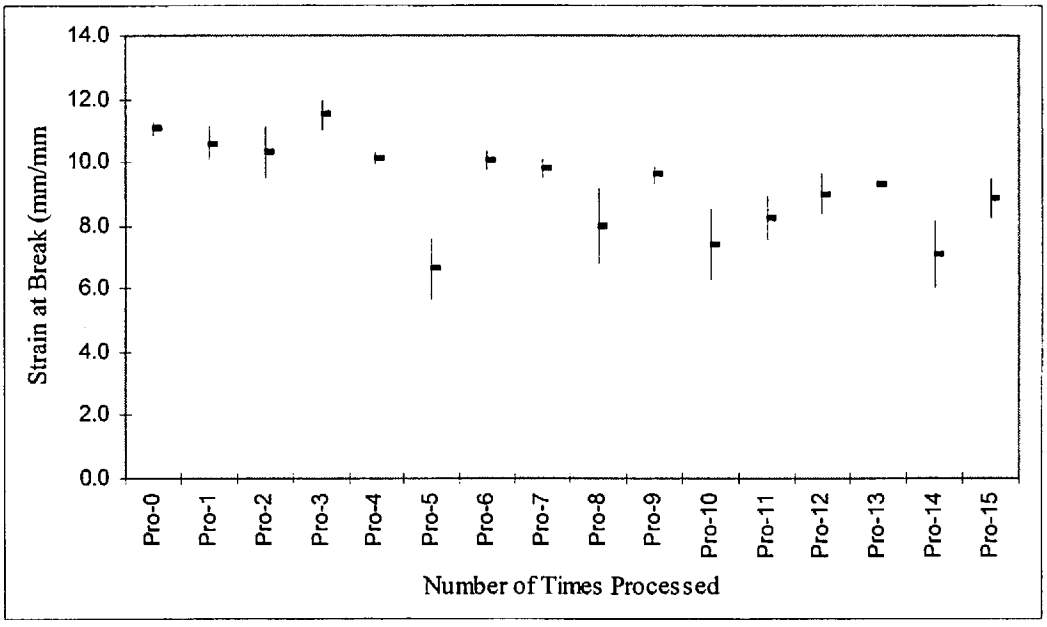
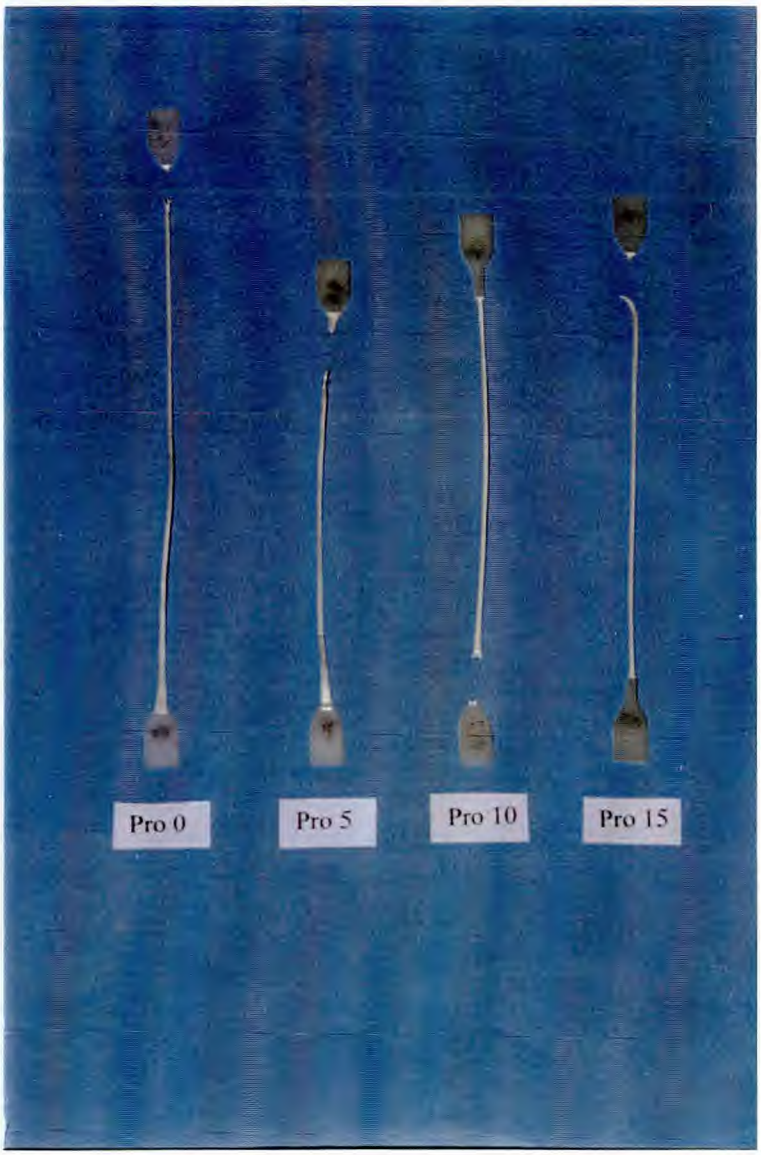


Table 4.2: Statistical analysis of tensile strength results.

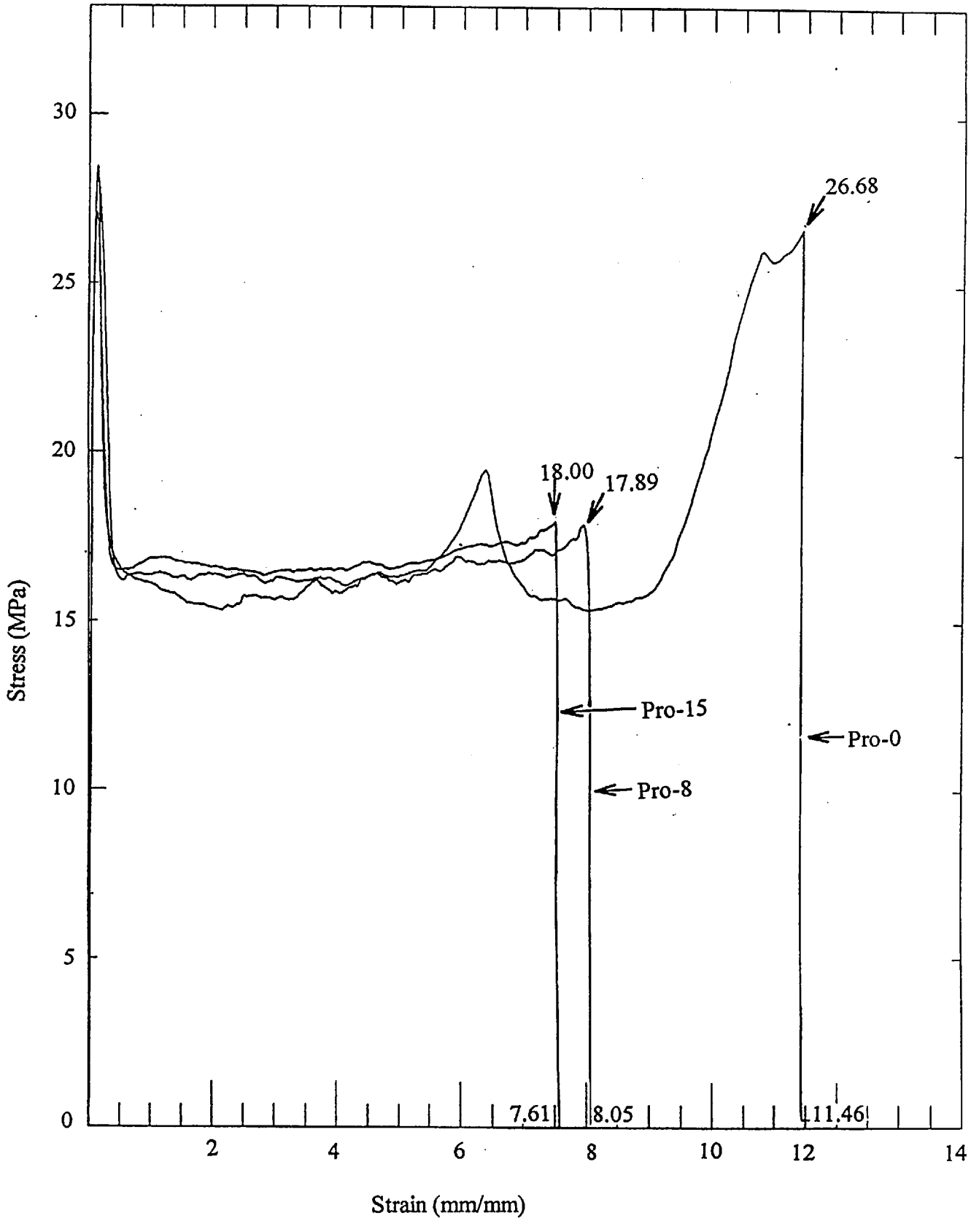
Tensile variables	**Pro-0 to Pro-4**		**Pro-5 to Pro-15**		**Level of change**	**p**
	Average	**SD**	**Average**	**SD**	**(Fall by:)**	
Stress at Yield (MPa)	**27.07**	0.47	**26.92**	0.45	**0.005 %**	**NS**
Stress at Break (MPa)	**23.54**	1.33	**12.32**	3.20	**47.00 %**	**$p < 0.01$**
Strain at Break (mm/mm)	**10.72**	0.56	**8.55**	1.15	**20.00 %**	**$p < 0.05$**

Photograph 4.11: HDPE virgin dumb-bell specimens extruded successively up to 15 times and tested in tension for determining their tensile strengths.



Stress at break and strain at break averages for Pro-5 to Pro-15 decreased by 47% and 20% from their corresponding averages for Pro-0 to Pro-4, respectively. This deterioration is strongly indicated as the colour of the virgin HDPE became progressively yellow with increasing numbers of extrusions (Photograph 4.4 in sub-section 4.2.4 and Photograph 4.12 in sub-section 4.4.3). Figure 4.7 shows this degradation in tensile strength more clearly by plotting tensile stress values against their strain values.

Figure 4.7: Strain vs. Stress curves for the HDPE: virgin (Pro-0), 8 times processed (Pro-8), and 15 times processed (Pro-15).

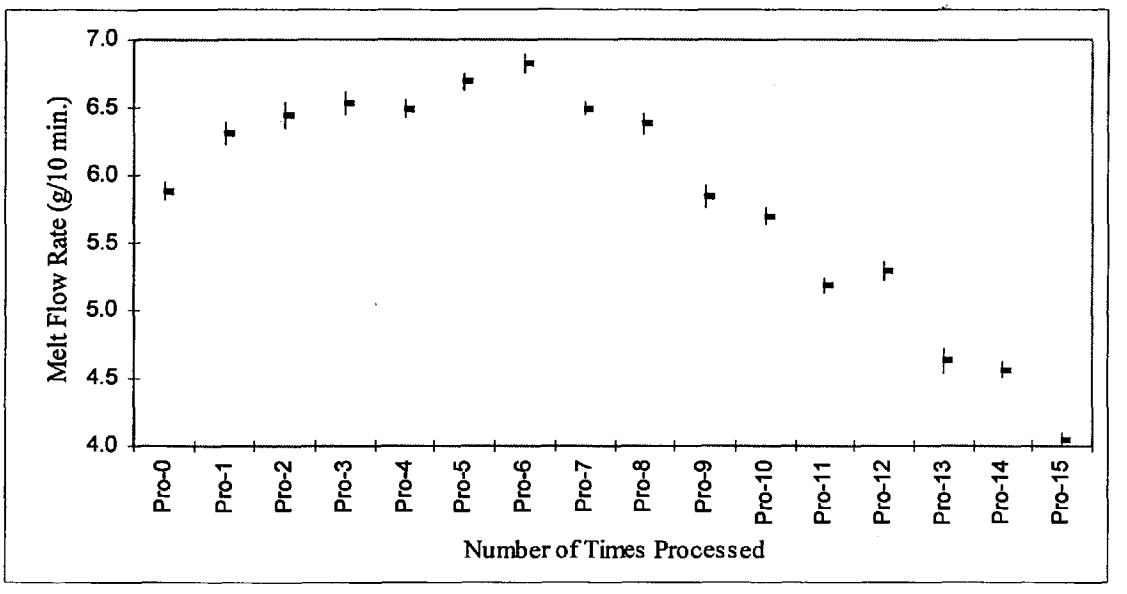


This decrease in tensile strength with increasing number of in-house successive processings was also reported in an in-depth study carried out by Williams and Bevis (1980b). In this respect a detailed discussion is made in Chapter 7. Likewise in another study performed by Ram and Getz (1984), a decrease in break properties in the course of repeated extrusions up to 3 times was indicated when virgin low density polyethylene (LDPE) was subjected to intensive shearing which probably depends on the shear rate. They also reported that strain at break *normally increases upon increasing molecular weight but diminishes with the appearance of gel.* Gels are highly porous three dimensional network structures based on polymeric molecules forming while reprocessing (Walker, 1995).

4.4.2 Melt Flow Behaviour

Figure 4.8 illustrates the pattern of changes in melt flow rate (MFR) of virgin HDPE determined against their corresponding number of times of processing. MFR values started with 5.9 g/10 min for Pro-0, increasing up to a maximum of 6.8 g/10 min around Pro-6 and thereafter decreasing to the lowest value of 4.1 g/10 min determined for Pro-15 material.

Figure 4.8: Effect of successive extrusion on MFR of virgin HDPE (± SE).



The results from the Duncan's New Multiple-Range Test (Steel and Torrie, 1980) confirms that the change in the MFR value of Pro-0 is significant (Table 4.3). Such changes in this rheological property of Pro-0 material are probably mainly due to the cumulative thermal effects in the course of successive processings. This is because of the shearing effect on the materials is minimal, following the fact that these had been extruded successively using a twin screw extruder at a low speed (4-5 rpm) coupled with a low temperature (197 ^{0}C) and short retaining time (2-3 min).

Table 4.3 : Summarised results from the Duncan's New Multiple-Range Test.

From the Figure 4.8:		
Pro-6 a		**Note:** 1) Process numbers with the same letters are not significantly different in their MFR at P<0.05.
Pro-5 ab	Pro-7 c	
Pro-4 c	Pro-8 c	
Pro-3 bc	Pro-9 d	2) Order of process numbers as in the first column of this Table is used for convenience to compare with the distribution of MFR values in Figure 4.9.
Pro-2 c	Pro-10 d	
Pro-1 c	Pro-11 e	
Pro-0 d	Pro-12 e	
	Pro-13 f	
	Pro-14 f	
	Pro-15 g	

MFR is normally increased with the increase of successive processings number. This has happened in accordance with a decrease in both stress and strain at break due to chain scission and thus a reduction in molecular mass resulting from the mechanical and/or thermal effects during reprocessings (Walker, 1995; Williams and Bevis, 1980b). More discussion on this increase in MFR determined by the previous works is made in Chapter 7.

If decrease in MFR occurred due to the effect of crosslinking, there would have to be an increase in gel content in solution for Pro-15 material. The decrease in stress at break (mentioned above) and also a reduction in impact resistance (mentioned below) as observed in this study suggest that no crosslinking in polymer chain has occurred as a result of successive processings. If this is the case, the present study would have a decrease, instead of increase, in gel content in solution for Pro-15. However, gel determination could not be done in the present study due to time constraints.

Therefore, the decrease in MFR in the second part of the trend shown in the Figure 4.8 is not generally expected, although these MFR values appear to be real, considering their small standard errors. In addition, since MFR test is a crude form of traditional test method, it cannot be expected to achieve around 100% accuracy in MFR results. For instance, MFR value of a handful amount of a particular batch of HDPE taken from a sack is likely to differ from that of another handful amount taken from the same sack (Dyson, 1997).

Thus the trends of initial increase of MFR and then decrease with the number of successive extrusions (as shown in the Figure 4.8) are still in question, which requires further study. However, the results from literature review suggest that there are some previous works which reported a decrease in MFR values of both the LDPE and HDPE against their successive processings number (See Chapter 7).

4.4.3 Impact Strengths

In Table 4.4, the results of impact force and deflection required to initiate fracture reveal that the virgin HDPE (Pro-0) required less energy to fracture than its 15 times extruded material (Pro-15). This means that Pro-0 is less resistant to impact fracture than Pro-15. It has also been confirmed by the energy values, E1, required for deflection of fracture.

Their performance in resisting deformation (stiffness factor) can be calculated as follows:

$$\text{Stiffness factor or modular factor} = \frac{\text{Force}}{(\text{Distance or deflection})^3}$$

which is 1.37×10^{-3} and 1.24×10^{-3} for Pro-0 and Pro-15, respectively. Thus, depending on the insignificant difference between these two stiffness factors, there is hardly any change in their impact strength up to 15 times of processing.

Table 4.4: Summarised results from the impact strength tests for Pro-0 and Pro-15.

Notations for replicates and variables	Force required to initiate crack (kN)	Deflection or distance (mm)	Energy required for deflection, E1 (J)	Total energy required, E2 (J)	Energy required for crack propagation E2 - E1 (J)	Toughness assessment factor, (E2-E1)/E1
Pro - 0#: 1	2.28	11.73	11.87	18.49	6.62	0.56
2	2.42	12.24	13.34	16.73	3.39	0.25
3	2.32	11.72	12.35	19.39	7.04	0.57
4	2.48	12.66	14.35	21.81	7.46	0.52
5	2.27	11.53	11.48	16.46	4.98	0.43
Mean	**2.35**	**11.98**	**12.68**	**18.58**	**5.90**	**0.47**
SD	*0.09*	*0.46*	*1.17*	*2.18*	*1.69*	*0.13*
SE	*0.04*	*0.21*	*0.52*	*0.98*	*0.75*	0.06
CV	*4%*	*4%*	*9%*	*12%*	*27%*	
Pro-15#: 1	2.75	12.91	16.32	19.87	3.55	0.22
2	2.92	13.35	18.72	22.96	4.24	0.23
3	2.87	13.38	18.23	22.39	4.16	0.23
4	2.75	12.78	16.67	19.86	3.19	0.19
5	2.84	13.39	18.03	21.31	3.28	0.18
Mean	**2.83**	**13.16**	**17.59**	**21.28**	**3.68**	**0.21**
SD	*0.08*	*0.29*	*1.04*	*1.42*	*0.49*	*0.02*
SE	*0.03*	*0.13*	*0.47*	*0.63*	*0.22*	0.01
CV	*3%*	*2%*	*6%*	*7%*	*13%*	
t-cal between for Pro-0 and Pro-15 =	8.91**	4.83**	7.03**	NS	2.82*	**4.37****

#Number of processing of Pro-0 and Pro-15 pellets was increased by one when these were moulded into plaque specimens. Since this moulding process is a part of preparing sample specimens, this increase in process number has been ignored for the purpose of maintaining their same identity in all cases.

*Significant ($P < 0.05$; $t_{crt} = 2.31$ at $\alpha = 95\%$ and $df = 8$);

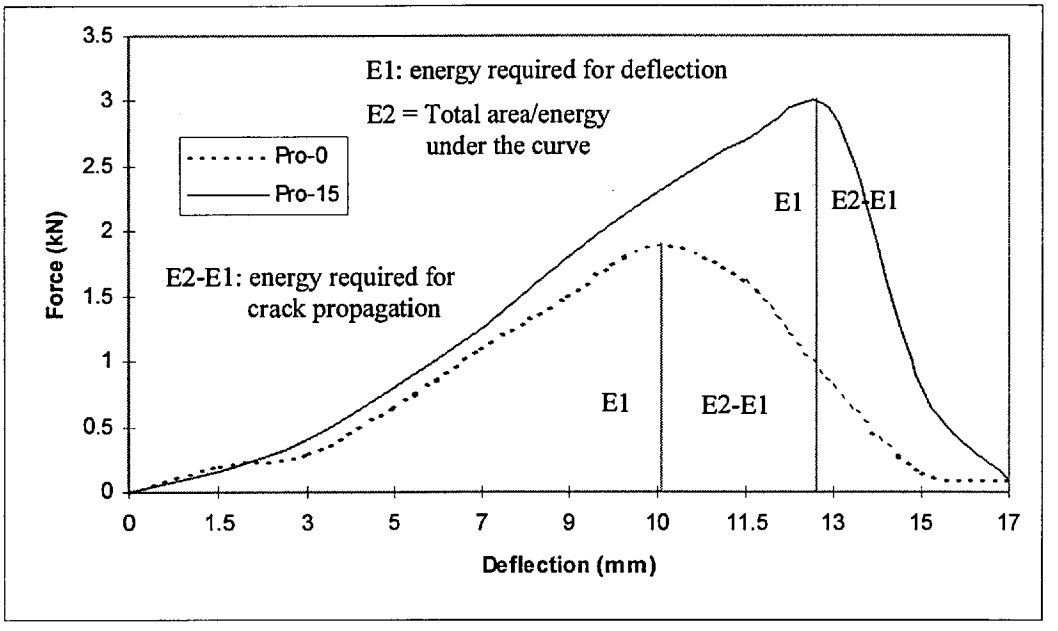
**Highly significant ($P < 0.01$; $t_{crt} = 3.36$ at $\alpha = 99\%$ and $df = 8$); NS = not significant

Considering total energy, E2, required for impact fracture and crack propagation, Pro-0 is more impact resistant than Pro-15 which can only be due to its greater "tear" resistance or resistance to crack propagation. This is confirmed by the difference in their crack propagation energy, E2 - E1 (Figure 4.9). The energy required for crack propagation of Pro-0 is greater than the energy required for Pro-15. It means Pro-0 has better crack propagation resistance. In other words, Pro-0 is tougher than Pro-15.

The difference between the values of toughness assessment factor, (E2 - E1)/E1, of Pro-0 and Pro-15 is also statistically significant as shown in Table 4.4. Their other impact strength parameters are also significantly different, except the total required for deflection and crack propagation. It indicates that the latter material lost its impact resisting capacity as evidenced by the difference in crack propagation pattern and

extent, and also, by the changes in their colour as a result of repeated extrusion (Photograph 4.12). This loss in toughness suggests that a decrease in molecular weight has taken place. Crosslinking would increase it.

Figure 4.9: Impact resisting properties of virgin and 15 times extruded HDPE: Force vs. Deflection.

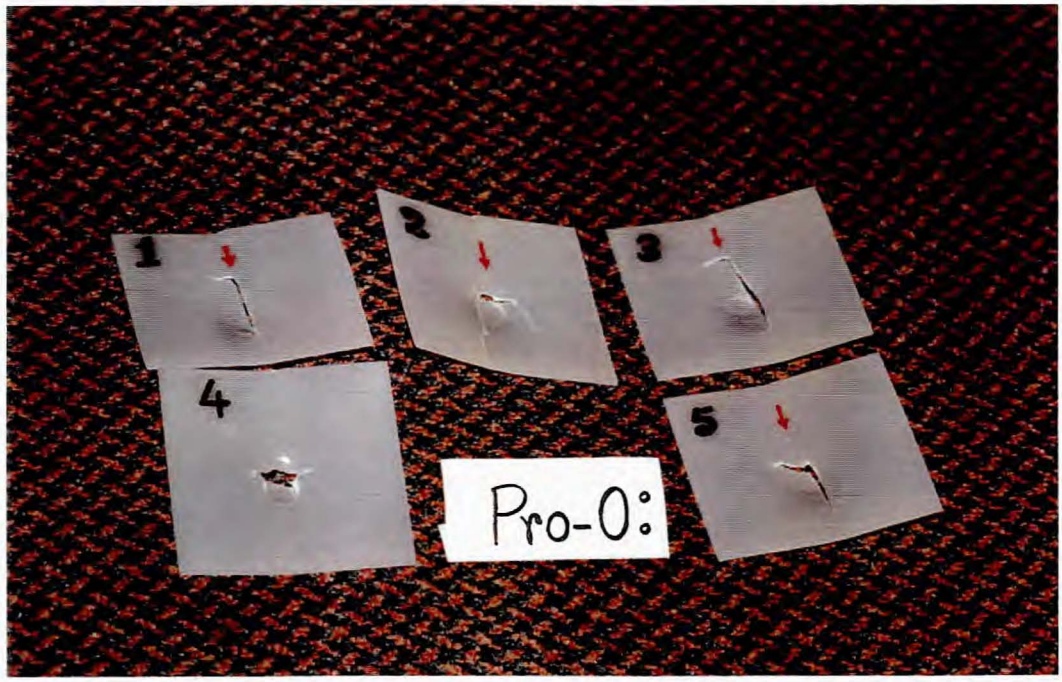


Pro-15 material required higher energy to fracture as it became brittle but relatively hard. Consistency in crack propagation pattern (all U-shaped) on the replicate plaque specimens of Pro-15 also supports its brittleness. Moreover, if a material is brittle, co-efficient of variation (CV), $\frac{\delta * 100}{\overline{X}}$, among the replicate results of its impact parameters would also be consistent. Consistency in this co-efficient for Pro-15 (3%, 6% and 7%) is relatively better than Pro-0 (4%, 9% and 12%).

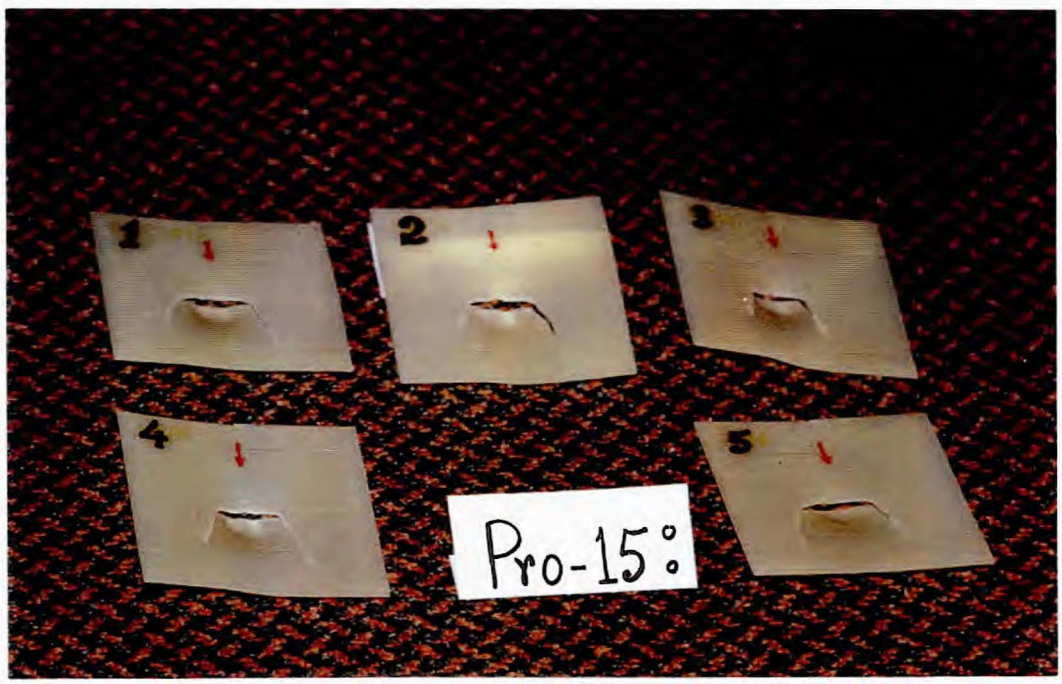
Overall conclusion is that considering all different impact parameters' results, Pro-15 is stronger or stiffer (more resistant to deformation) but less tough (i.e. more brittle) than Pro-0. It means Pro-0 is considerably tougher (i.e. less brittle) than Pro-15. Changes in colour from white to light yellowish brown are another indication of degradation due to successive processing. However, according to Dyson (1997), this change over fifteen times of processing does not necessarily represent a significant change in quality. The material may well be still fit for the purpose of bottle making.

Photograph 4.12: Impact strength tested plaque specimens with their fracture shape and crack propagation pattern (a) Virgin HDPE, Pro-0, and (b) 15 times extruded materials, Pro 15, of the virgin HDPE.

(a)



(b)



4.4.4 Viscosity - Flow Behaviour

a) Viscosity Vs. Shear Rate:

Table 4.5 summarises the melt flow behaviour of virgin pellets (Pro-0) and the pellets processed fifteen times (Pro-15). Their apparent viscosity, defined as shear stress over shear rates, was measured separately and then compared. The results indicate that both of the materials behave in similar manner. Hence, there was little change in molecular weight. Like most molten polymers - pseudo-plastics, such viscosity of these HDPE materials falls with increasing shear rates. In spite of these facts apparent viscosity values of Pro-15 in almost all cases are apparently higher than the viscosity values of Pro-0 at the same shear rates.

Table 4.5: Summary of the melt flow properties of Pro-0 and Pro-15 materials.

Materials	Speed			Pressure [1 psi = 6895 Nm^{-2}]			Shear stress[$] ($Nm^{-2}$)	Shear rate[£] (s^{-1})	Apparent viscosity (Nsm^{-2})
	Des.	(mm/ min)	(cm/s)	(psi)[#]	Ex.Error[#] (in %)	(Nm^{-2})			
Pro-0	Slow	4	0.0067	100	2.00 %	689500	21546.88	19.66	**1095.93**
		8	0.0133	137	1.46 %	944615	29519.22	39.32	**750.71**
		12	0.0200	161	1.24 %	1110095	34690.47	58.98	**588.15**
		16	0.0267	180	1.11 %	1241100	38784.38	78.64	**493.17**
	Fast	20	0.0333	200	1.00 %	1379000	43093.75	98.30	**438.37**
		40	0.0667	250	0.80 %	1723750	53867.19	196.61	**273.98**
		60	0.1000	290	0.69 %	1999550	62485.94	294.91	**211.88**
		80	0.1333	300	0.67 %	2068500	64640.63	393.22	**164.39**
Pro-15	Slow	4	0.0067	115	1.74 %	792925	24778.91	19.66	**1260.32**
		8	0.0133	146	1.37 %	1006670	31458.44	39.32	**800.03**
		12	0.0200	169	1.18 %	1165255	36414.22	58.98	**617.37**
		16	0.0267	186	1.08 %	1282470	40077.19	78.64	**509.61**
	Fast	20	0.0333	198	1.01 %	1365210	42662.81	98.30	**433.99**
		40	0.0667	254	0.79 %	1751330	54729.06	196.61	**278.37**
		60	0.1000	290	0.69 %	1999550	62485.94	294.91	**211.88**
		80	0.1333	320	0.63 %	2206400	68950.00	393.22	**175.35**

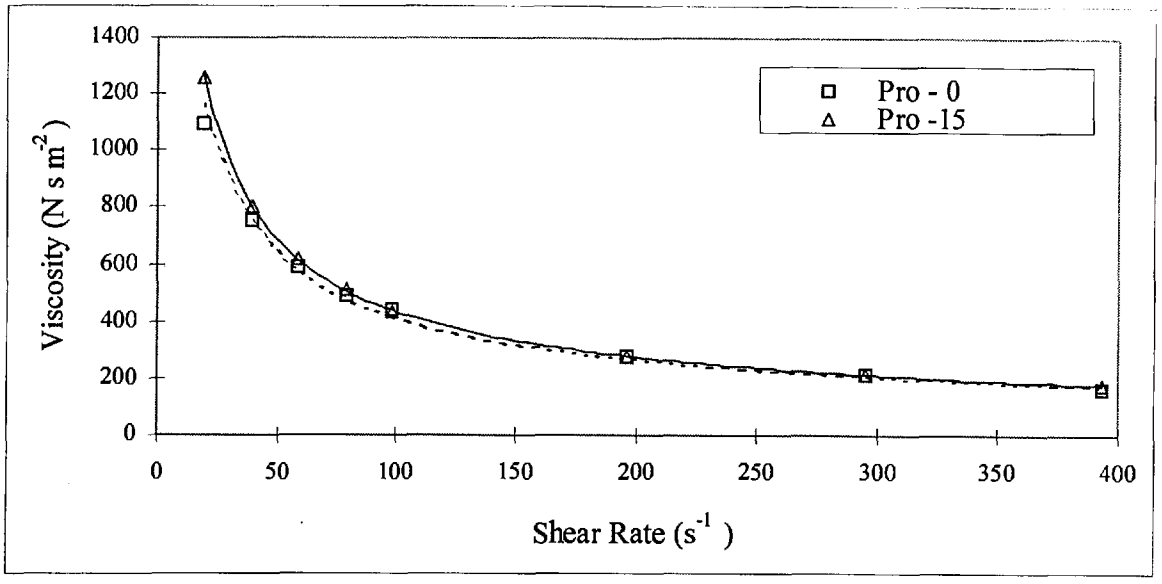
Notes: [#]Error estimated in reading all 'psi' observations on the scale of the Pressure Transducer used was about ±2.

[$]Shear Stress, $\tau = \frac{Pr}{2l}$ (in Nm^{-2}), [P - pressure (in Nm^{-2}); r -die hole radius (0.125 cm); l - die hole length (2 cm)].

[£]Shear Rate $= \frac{4Q_v}{\pi r^3}$ (in s^{-1}), [Q_v - volume flow rate = $\pi R^2 \upsilon$; R -cylinder bore radius (1.2 cm); υ - speed (in cm/s)].

Figure 4.10 shows initial rapid decrease in viscosity and then flattening off with the increase in shear rates. This phenomenon, which is the normal behaviour for polymer melts, is common for both of the Pro-0 and Pro-15 materials.

Figure 4.10: Apparent viscosity vs. shear rate curves for the materials processed "0 times" and "15 times" in London.



However, the initial difference between the viscosity results of Pro-0 and Pro-15 disappears immediately the shear rate increased although there is some indication of it being maintained up to the shear rate of 100 s^{-1}. Note that the proportion of error (as shown in percentage in Table 4.5) in reading pressure values on the gauge (minimum unit = 5 psi) of the pressure transducer used is high at slow speed and hence at the low shear rate. These errors are estimated from 2.00% to 0.63% at the speed of 4 to 80 mm/min, respectively.

Here it is also apparent that a higher precision in the viscosity results could have been achieved by either (i) repeating this viscosity test a few more times for both the materials in order to replicate the results obtained, or (ii) using a more sophisticated test machine which is more sensitive so as to be able to detect any visual change in polymer melts but such a machine was not available. As far as repetition of the test is concerned, it was not possible, because the amount of the materials required for performing at least five replicate flow tests could not ascertained before starting the laboratory experiment and thus there was a shortage of appropriate material available at this point in the study.

However, considering this experimental error, there is no significant difference between Pro-0 and Pro-15 values. Therefore, taking into account the role of experimental error, it can be suggested that there is hardly any difference between the viscosity values

of Pro-0 and Pro-15 materials, which is reinvestigated in the following sub-section by giving proportionate weight to log of shear stress values against their corresponding log of shear rates.

b) Shear Stress vs. Shear Rate:

It is believed that *intercept* (k) and *slope* (n) of the following '*power law*' (Brydson, 1981) for any two polymers should be the same if the materials possess the same molecular weight (Dyson, 1997). It also depends on their molecular distributions.

The Power Law: $\tau = k(\gamma)^n$

where,

τ is shear stress,
γ is shear rate,
k is a constant, and
n is slope or power index.

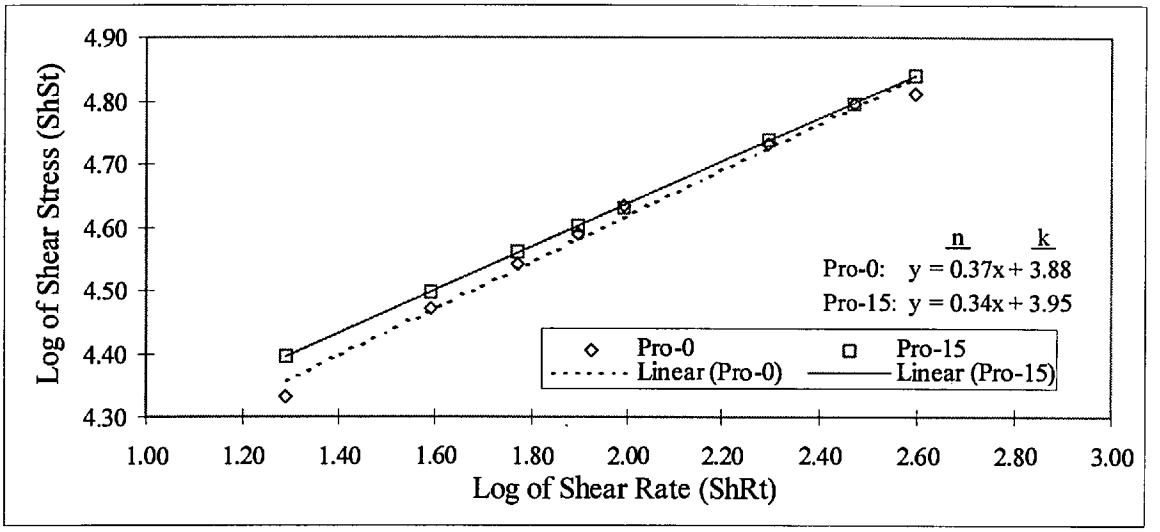
This power law equation may be written in logarithmic form as follows:

$$\log \tau = \log k + n \log \gamma$$

Following this logarithmic equation, it is generally known that log-log plots of shear stress, τ, versus shear rate, γ, will yield a straight line. In addition, difference between molecular weights of two different polymeric materials can be identified by comparing the slopes, n, of two linear lines generated from their log-log plotting of shear stress vs. shear rate. Similarly, difference between their molecular weights can also be identified by comparing the intercept, k, of those two linear lines. If there is no difference between their molecular weights, both the values of 'n' and 'k' of a material would be same or very close to the corresponding values of the other material. The slope for a material is inversely related to its molecular weight (mw) and apparent viscosity (η) (Dyson, 1997). The lower the slope value, the higher the molecular weight ($\downarrow$'n' $\approx$ $\uparrow$'mw' $\approx$ $\uparrow$'η' or $\uparrow$'n' $\approx$ $\downarrow$'mw' $\approx$ $\downarrow$'η'). Whereas the intercept value is directly related to molecular weight (mw), i.e. the lower the intercept value, the higher the molecular weight ($\uparrow$'k' $\approx$ $\uparrow$'mw' $\approx$ $\uparrow$'η' or $\downarrow$'k' $\approx$ $\downarrow$'mw' $\approx$ $\downarrow$'η'). However, *the slope, n, is more important than intercept, k,* in identifying difference between molecular weights of two different polymers (Dyson, 1997).

In the present study, Pro-0 material was hypothesised to be different from the Pro-15 material and their difference in molecular weight can be determined by calculating the n and k values of two straight lines derived from their log-log plots of 'τ' versus 'γ' (Figure 4.11).

Figure 4.11: Log-log plots of shear stress, τ vs. shear rate, γ, of Pro-0 and Pro-15 materials processed in London.



In Figure 4.11, the slope (n = 0.37) of the straight line (or regression line) for Pro-0 is greater than the slope (n = 0.34) of Pro-15. Differences between the slopes of these two independent regression lines were evaluated by performing *F-test* (Steel and Torrie, 1980) and are summarised in Table 4.6. The results of the test show that there is no significant difference between the slopes of the lines. Therefore, the decrease in the slope values (from 0.37 for Pro-0 to 0.34 for Pro-15) is not significant, which means that molecular weight of Pro-15 does not increase substantially over Pro-0, even following the cumulative thermal effects resulting from the successive extrusions. However, this insignificant increase or lack of change in molecular weight and hence very little increase in apparent viscosity, is suggested by the decreasing trend in MFR after six times processing, but it contradicts some of the results obtained from both the impact and tensile tests.

While comparing the intercept values of the lines, the value of k = 3.95 for Pro-15 is greater than the corresponding value of 3.88 for Pro-0. This increase in intercept value over the successive extrusions appears also to be indicative of a little increase in

molecular weight as indicated by the decrease in the slope mentioned earlier. That is molecular weight of Pro-15 has increased mostly due to the thermal effects during successive extrusions resulting in a insignificant increase in apparent viscosity.

Table 4.6: Comparison between the slope of the two independent regression lines of Pro-0 and Pro-15.

Materials	R^2	Slope		Intercept		SSreg	SSres	F (Calcu-lated)	*F* (critical)
		Coeff.	SE	Coeff.	SE				
Pro-0	0.990	0.372	0.015	3.872	0.031	0.192	0.002		*3.18* at
Pro-15	0.999	0.345	0.003	3.946	0.005	0.165	0.00005	**3.062**	df = (1,12)
Pro-0,15#	0.989	0.359	0.010	3.909	0.021	0.357	0.004		and α =95%

Notes:

R^2 = Coefficient of regression correlation, Coeff. = Coefficient, SE = Standard error, SSreg = regression sum of square, and SSres = Residual sum of square [were measured using *Quattro Pro for Windows, Version 5*: =>Tools=>Analysis Tools=>Advanced Regression Tool, Y:X.

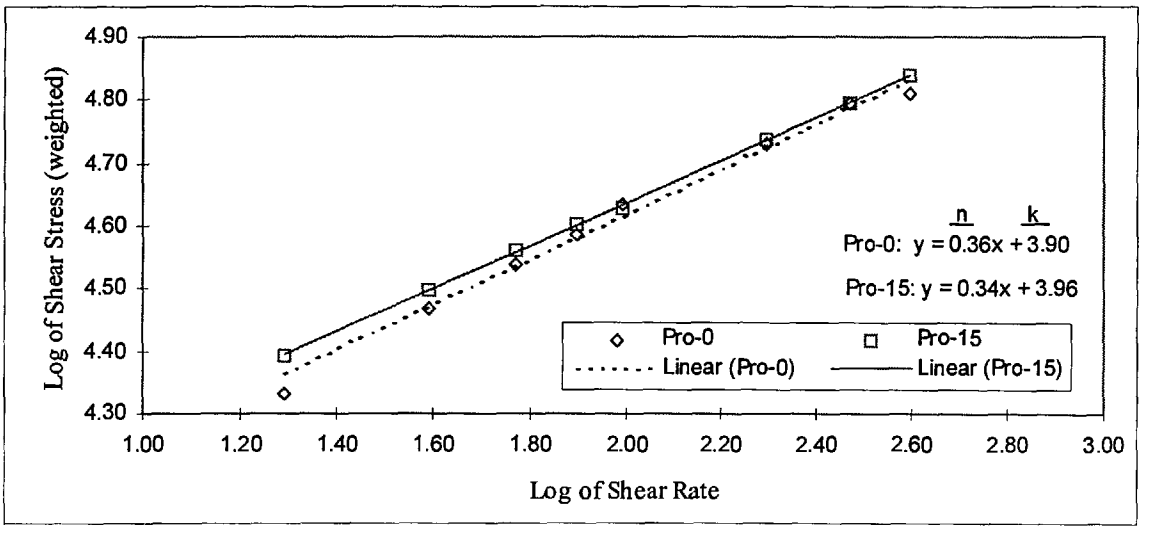
F = Total between regression significance

= [(SSreg0 + SSreg15 - SSreg0,15) x (n0 + n15 -4)] / (SSres0 + Ssres15)

(Source: Steel and Torrie, 1980)

Data values of Shear Streass of Pro-0 and Pro-15 were plotted together.

Figure 4.12: Revised form of the Figure 4.11, considering *weighted number of data points plotting* for log of shear stress against their corresponding increasing log of shear rate values.



Since shear stress values at higher shear rates experienced relatively lower errors than those measured at lower shear rates, more weight is allocated to the former cases, following the reasons and procedure as discussed in Appendix 4.2. By plotting weighted number of data points, a revised form of Figure 4.11 is obtained with two more or less identical straight lines with much closer slope values (0.36 and 0.34) and intercept values (3.90 and 3.96) for the Pro-0 and Pro-15 materials, respectively, as shown in Figure 4.12. It also shows that there is no significant difference, either in the slope or in the intercept and thus no change has occurred in molecular weight and apparent viscosity due to successive extrusions.

However, the net result of these current viscosity measurements is that there is not much difference between Pro-0 and Pro-15 and if anything, the molecular weight of Pro-15 is higher than that of Pro-0 as indicated by the decrease in slope value.

4.5 General Discussion

Effects of in-house successive reprocessings on the polymer properties are not straightforward as had been hypothesised at the beginning of the current study. However, it is evident that there are a good many hidden reasons involved which cause some changes or anomalies in the properties of the HDPE in the course of its successive reprocessings. To explore these reasons and to minimise any contradiction in the prevailing understanding about the effects of reprocessing on the HDPE, further basic studies with a considerable number of replicated samples are required.

Following contradiction in some cases of the results obtained and discussed in this Chapter, it is considered here that whatever the extent of changes occurred in the properties of HDPE due to the effects of 15 times processing this is very little. There would be almost no change in properties if the test materials and the machines behaved consistently. In practice, nevertheless, this small change in properties is very important and it may become catastrophic in the case of large scale commercial plastics processing. This is because of difficulties and expense in maintaining consistency of

operation for a large volume of recovered plastics and degradation due to the presence of unwanted material which is very likely in a large scale recycling process.

However, all of the machines used in the laboratory experiments of this study are quite similar in all respects except their production capacity to the machines used by the UK plastic processing industries. Therefore, the results discussed in this Chapter can be equally applicable in determining future recycling strategies for the UK (Chapter 7). In addition, these results for mechanical and rheological properties of the virgin HDPE determined under *known processing conditions* in London have been compared with those results determined for the same virgin HDPE reprocessed under *unknown processing conditions* in Dhaka (See Chapter 5).

Summary:

- Virgin HDPE starts behaving differently after extruding successively more than 4-6 times;
- Stress at yield of this material remains more or less unchanged;
- There is a severe fall in stress at break from 23.5 to 12.3 MPa after 4 times extrusions. Interestingly, there is also a shallow fall in strain at break from 10.7 to 8.55 mm/mm after 4 times extrusions;
- MFR initially increases up to a value of 6.8 g/10 min at 6 numbers of processing and then decreases to a minimum of 4.1 g/10 min at 15 numbers of processing;
- The materials become more brittle but stronger (more resistant to deformation) in the course of successive extrusions. Deterioration in colour is also visible;
- Increase in molecular weight and thus increase in viscosity due to several processings might have happened for the virgin HDPE tested as is suggested by the decrease in MFR and increase in impact fracture resistance but it is contradicted by the fall in stress at break, strain at break, crack propagation resistance and toughness assessment factor.

CHAPTER 5:

Properties of HDPE Recycled and Reprocessed in Bangladesh and India

5.1 Introduction

The major theme of this chapter is to explain the effect of recycling on the properties of High Density Polyethylene (HDPE) recovered from the waste streams of Bangladesh and India. This Chapter covers the methods of properties determination, results, analysis and discussion. As in the case of the sample specimens prepared from the successively extruded virgin HDPE in London (Chapter 4), the sample specimens prepared out of the general scraps collected from Bangladesh and India were also tested in the laboratory of the School of Polymer Technology, University of North London, London.

Attempts have been made to compare between the effects of the successive extrusions on the properties of the virgin HDPE under the known processing conditions and the effects of the successive extrusion-blow-moulding on the same materials under the unknown processing conditions. Some efforts have been made to investigate if there are any significant differences in the properties of the HDPE collected from two different countries, which might arise from regional differences in the existing recycling systems and their efficiency.

All these recovered general scraps have been in use and re-use under tropical environmental conditions and subjected to tremendous stresses of intensive use for different duration according to their number of recyclings in Bangladesh and India. A small initiative was also taken to estimate the level of weathering effects on the quality of the recovered HDPE.

5.2 Experimental Details

5.2.1 Materials

A total of 9 different batches of HDPE, 1 batch of virgin and 8 batches of general scraps collected from the Dhaka plastic market of Bangladesh, were extrusion-blow-moulded

in Dhaka (subsection 3.4.1 in Chapter 3) and tested to measure some of their mechanical and rheological properties in London. In the case of the first batch, a known grade of virgin HDPE commonly used in Dhaka was collected and used in this study as a reference material. This virgin material was the same material used for the successive extrusion in London (Chapter 4). Another 3 batches of materials were also prepared and tested, one of which (2B) was separated from the processed once scraps (2A) and another two batches (3B and 3C) were derived from the processed twice scraps (3A). A detailed explanation of the features of all these 1+8+3 = 12 batches of HDPE has already been made in the Chapter 3 (Figure 3.4 and Table 3.6 in Chapter 3), with respect to their physical appearance, general quality, possible source of origin, probable number of times processed and recycled, and notations of the sample specimens used in this study (Table 3.6). A total of 6 batches of virgin and scrap HDPE, 3 batches each, from Calcutta and Delhi plastic markets of India were also tested.

5.2.2 Extrusion-blow-moulding

Altogether 12+6 = 18 batches of HDPE were successively moulded into 2 litre jerry-cans using a single screw extrusion-blow-moulding machine in Dhaka (section 3.4 in Chapter 3). These successive mouldings were carried out in-house, commencing with extrusion-blow-moulding 10 kg of the virgin HDPE (Pro-0) up to 7 times.

Following the procedures as detailed in subsection 3.4.4 of Chapter 3, sample jerry-cans were collected from the lot of jerry-cans made of Pro-0, and all the jerry-cans remaining were granulated and fed into the moulding machine for the next successive moulding. This whole procedure was repeated for each of the 12 batches of materials from Dhaka for different number of times, which gave a total of 50 batches of jerry-cans (Table 3.6 in Chapter 3). Following the same moulding procedures as in the case of the Dhaka materials, another 6 batches of jerry-cans were moulded out of the materials from India (Table 3.8 in Chapter 3), and sample jerry-cans were collected for laboratory tests in London. No successive processing was performed for these materials due to the lack of available time and resources involved.

5.2.3 Cutting Sheets from Jerry-cans and Labelling

Five replicate sheets, one sheet per jerry-can, were cut off from their middle back part for each of the 50+6 = 56 batches of jerry-cans. All sheets were labelled with their corresponding batch number and letter for derivation, if any, followed by their total number of times processed during the past life of recycling and in-house successive reprocessing carried out in this study. A batch number within the first bracket has been used for the material from Bangladesh and without any bracket for the material from India. For instance, a sample notation such as (2A)/3 means that this is a thrice processed first derivative of 2nd batch material from Bangladesh.

5.2.4 Cutting Dumb-bells and Flakes from Sheets

Five dumb-bells from the five replicate sheets were punched for each of the 56 batches of materials processed for the different number of times. The dimensions of the dumb-bells were: (a) overall length = 75 mm, (b) width of ends = 12.5 $\pm$ 1.0, (c) length of narrow parallel portion = 25 $\pm$ 1.0, and (d) width of narrow parallel portion = 4.0 $\pm$ 0.1. Thickness was measured by a micrometer at the middle and two ends of the narrow parallel portion of all 56 x 5= 280 dumb-bell specimens and the measurements were recorded for determining tensile strength.

For the purpose of melt flow test, the remaining portions of the replicate sheets were cut into small flakes and mixed to make a composite sample for each batch of the materials under investigation.

5.2.5 Moulding Plaques

Plaque specimens for impact test were injection moulded only for the HDPE general scraps from Bangladesh using 'PECO 50 ton' injection moulding machine in London. The dimensions of the plaques were 8.75 x 8.75 x 1.5 mm. The machine was pre-heated for two hours before starting moulding. The processing temperatures of all of the general scraps were 225/230/235 ^{0}C at the three different zones on the machine.

According to the requirement of the materials under processing, pressure had to be changed which was within the range of 10.5 - 11.5 x 10^5 Nm^{-2}. Plaques were labelled immediately after collection. The machine was purged through before the start of moulding with a new batch of material.

5.3 Testing Procedures

5.3.1 Tensile Tests

Five replicate dumb-bell specimens from each of the 56 different batches of sheets were tested in tension on an Instron 1122 tensile strength testing machine at a cross head speed of 100 mm per minute, a full scale deflection of 200 N and a chart speed of 100 mm per min. The same tensile test procedures as described in subsection 4.3.1 of Chapter 4 were followed.

5.3.2 Melt Flow Rate Test

Melt flow rate (MFR) tests of 56 different batches of composite sample flakes were performed using a Davenport Sl. No.: 851 MFR testing machine fitted with a mechanical piston in a cylinder bore plugged with a die of diameter 2.09 mm. The British Standard Test Method 720A:1979 was followed (BSI, 1997b). The materials under test were in flake and pellet form. Before starting the test procedure, the machine was pre-heated for an hour with a melt temperature set at 190 ^{0}C. The remaining parts of this MFR test procedure followed in this case were same as the procedures elaborated in subsection 4.3.2 in Chapter 4.

5.3.3 Impact Test

The impact strengths of all 12 batches of materials collected from Dhaka were measured, using 5 replicate plaque specimens per batch. These tests were carried out according to the procedure as explained in subsection 4.3.4 of Chapter 4. This test was not possible to perform for the materials collected from India, because necessity of

this test for these materials had not been envisaged and thus there was a shortage of material required for replicate tests.

5.4 Results and Discussions

5.4.1 Melt Flow Rates (MFR)

Table 5.1 illustrates the MFR of a batch of virgin HDPE, 8 batches of HDPE general scraps and 3 batches of their derivatives against their number of times processed previously in the close-loop recycling system of Bangladesh. It also shows their MFR vs. in-house successive number of processings in the columns. Any general trend of change in MFR due to the effect of in-house successive moulding is also symbolised at the bottom row of the Table 5.1 using " ↓ " for decrease, " ↑ " for increase and "S" for remaining the same over all.

Figure 5.1 shows the MFR of the general scraps against their number of times processed previously under the existing recycling system. The waste materials processed previously 6, 8, 10, 12, and 13 times, which were not collected as sample, are denoted here with the notations beginning with "(..)" (i.e. no sample batch number given) followed by number of processings. This is due to the fact that, according to the existing recycling system in Dhaka, reclaimed scrap plastics processed previously for lower number of times (i.e. less than 5 times) are just shredded into flakes and used straightaway in moulding new products. However, in the case of those scraps processed previously for higher number of times (i.e. 5 times or more) these are required to be pelletised or granulated once or twice (depending on their impurity contents) before using them for moulding. As a result, for example, recycling of a batch of scraps with 5 processing number involves an intermediate melting stage of pelletising (6 number of processings), and after moulding stage, end up with 7 times processed recycled products after moulding. Therefore, this batch of 6 times processed pellets was not collected as sample in this study, because pellets are intermediate products rather than the final products (i.e. discarded scrap plastics) of a closed-loop recycling cycle.

Table 5.1: **MELT FLOW RATE** of the HDPE **virgin** and **general scraps** successively recycled and reprocessed in Dhaka, Bangladesh (g/10 min).

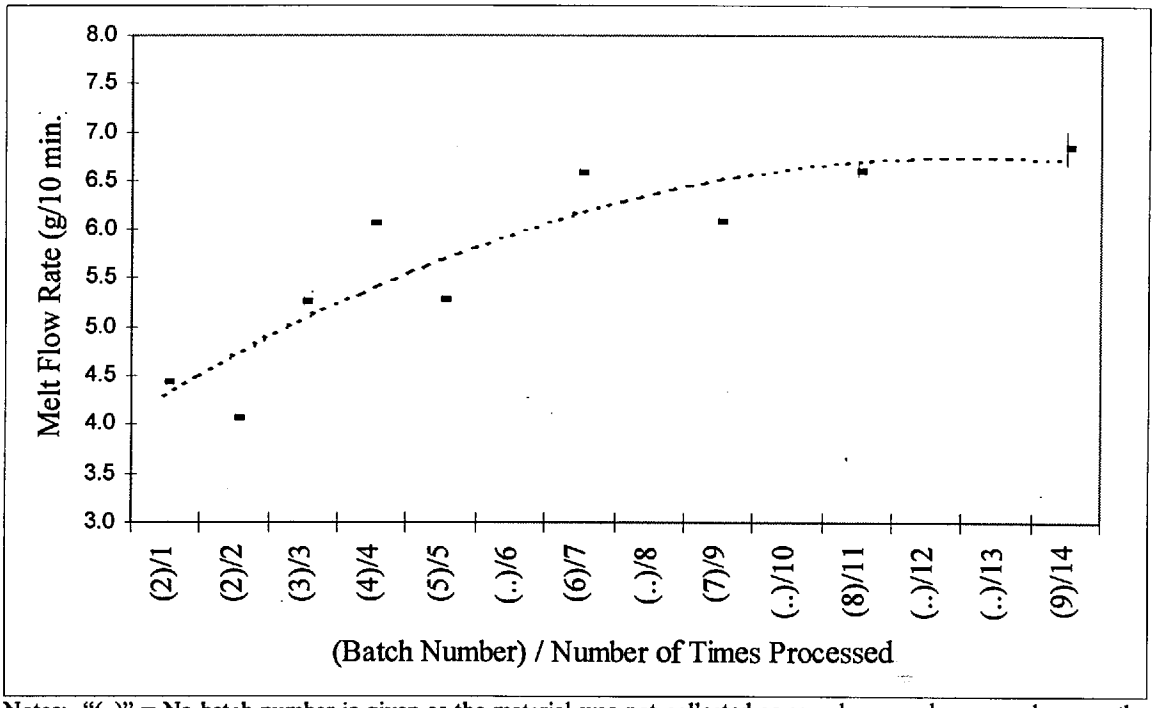
Number of times processed within the factory premise ↓	**Description of the Feedstocks and Their Position According to the Number of Times Processed in the Real Environment**											
	Translucent virgin pellets observed : **Pro.– 0 Recy.– 0**	Translucent flakes (of short life articles) : **Pro.– 1 Recy.– 0**	Same waste stream of [2A] but of long life articles: **Pro.– 1 Recy.– 0**	Translucent pellets (of short & long life articles & fractions): **Pro.– 2 Recy.– 0**	3A, but washed twice & colour flakes removed before pelletising: **Pro.– 2 Recy.– 0**	3A, but chaff won before pelletising: **Pro.– 2 Recy.– 0**	Pellets (milky coloured): **Pro.–3 Recy.– 0**	Granules (brown coloured): **Pro.–4/ 5 Recy.– 1**	Granules (dull-brown coloured): **Pro.– 6/7 Recy.– 2**	Granules (black coloured): **Pro.– 8/9 Recy.– 3**	Granules (dull-black coloured): **Pro.–10/11 Recy.– 4**	Granules (very dull-black colour: **Pro.–13/14 Recy.– 5**
Batch No. →	(1)	(2A)	(2B)	(3A)	(3B)	(3C)	(4)	(5)	(6)	(7)	(8)	(9)
Pro. 0	5.79											
Pro. 1	5.31	4.45	4.29									
Pro. 2	5.33	4.08	3.63	5.24	4.39	4.95						
Pro. 3	4.83	3.66	3.65	5.26	4.81	4.87	5.71					
Pro. 4	4.70	3.69	3.85	5.31	4.56	4.83	6.07	5.51				
Pro. 5	4.63	3.41	4.13	5.33	4.71	4.76	5.93	5.29				
Pro. 6	4.81	3.36	3.95	5.22	4.73	4.77	6.33	5.45	5.89			
Pro. 7	4.84	3.50	3.84	5.16	4.84	4.85	6.36	5.49	6.59			
Pro. 8							6.49	6.03	6.95	6.01		
Pro. 9									6.99	6.09		
Pro. 10										6.10	6.31	
Pro. 11											6.61	
Pro. 12												
Pro. 13												6.57
Pro. 14												6.84
COMMENT	↓	↓	S	S	S	S	↑ (S)	S	↑	S	S	S

Notes: Successive processings already performed in the past recycling cycles.

Notes: In-house successive processings had not been performed.

Notes: ↓ - decreases; ↑ - increases; S - remains the same.

Figure 5.1: **Melt flow rates** of the HDPE **General Scraps** against their number of times processed by the existing recycling system in Dhaka, Bangladesh (±SE).



Notes: "(..)" = No batch number is given as the material was not collected as sample general scrap as because the material processed 6, 8, 10, 12, or 13 times was not available in the form of scrap rather than in the form of pellets or granules. For convenience, some of the notations have been generalised as follows: (2)/1⇐ (2A)/1, (2)/2 ⇐ (2A)/2, (3)/3 ⇐ (3A)/3].

There is a steady increase, allowing for experimental error, in the MFR of the general scraps as the number of processings increases in the existing recycling system (Figure 5.1). With the cumulative effect of this system, the MFR value of the very dull black scrap, (9)/14, which has probably been passed through 14 melting processes and 5 cycles of recycling in the tropical conditions, has been increased by 29% of the MFR value measured for the once processed virgin HDPE , (1)/1 (Table 5.1).

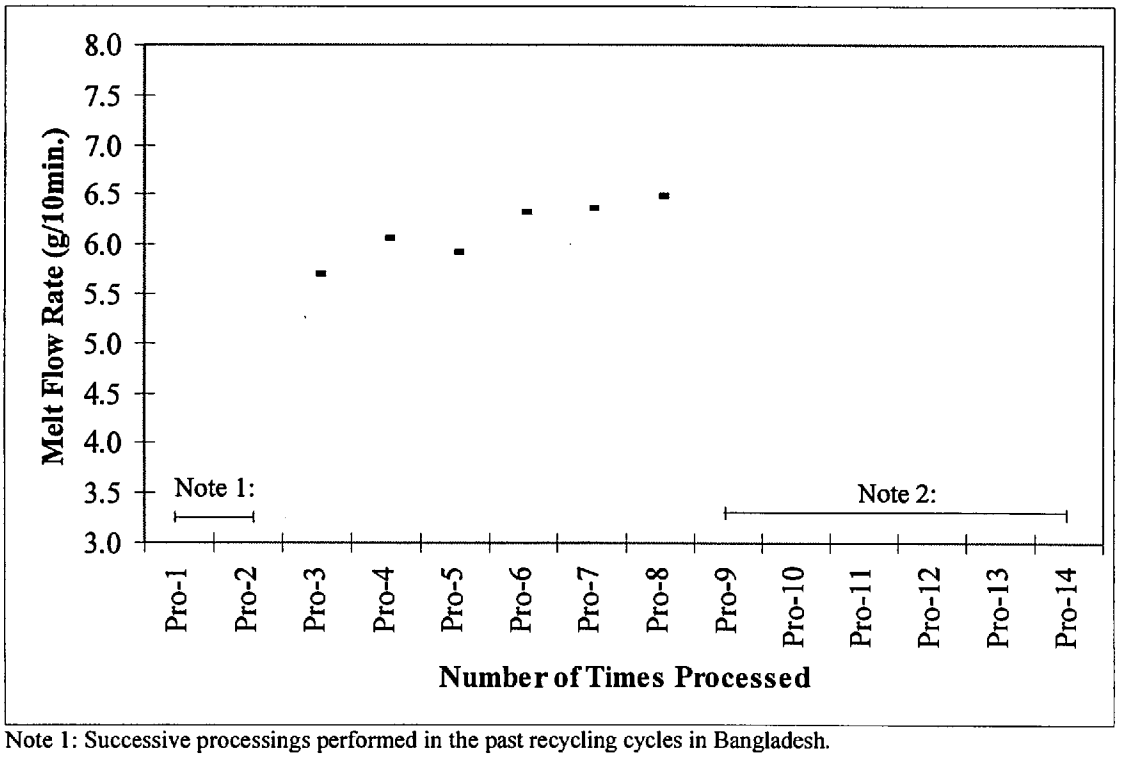
On the basis of the laboratory test results with low standard errors and the distribution of the error bars in the Figure 5.1, it is clear that this increase is statistically significant. This increase in MFR of the scrap materials may be attributed to the fact that a higher proportion of impurities is probably included cumulatively into the material recycled for a higher number of times. In addition, degradation of these general scraps may also be due to both the mechanical and thermal effects as the materials are generally reprocessed within the existing recycling system using single screw extrusion-blow-moulding machines. Single screw machines cause more shearing effects upon the feedstocks compared to the twin screw extruder used in London (Chapter 4). Moreover, the former machines are not fitted with any equipment to maintain consistency in the

screw's revolutions per minute, retaining time for feedstock in the barrel of moulding machine, melt temperature, and pressure of air blown.

In addition to the effect of impurities, two out of the total 12 batches of materials tested also experienced an increase in MFR following the effects of in-house successive moulding (Table 5.1). For example, MFR values of milky coloured pellets, (4)/3, and dull brown granules, (6)/6 have increased by 14% and 19% within a low number of in-house processings, respectively (Figures 5.2 and 5.3).

However, although the general expectation is that MFR of a polymeric material should increase with the increase of its processing number, there are some contradictory results obtained for two other materials, the virgin HDPE, (1)/0, and translucent flakes, (2A)/1. For these materials, MFR is *decreased* with the increasing number of in-house successive extrusion-blow-mouldings (Figures 5.4 and 5.5). Interestingly, a steady decrease in MFR is also experienced by the same batch of virgin HDPE , (1)/0, when it was successively extruded more than 6 times under the known processing conditions in London (Chapter 4).

Figure 5.2: **MFR** vs. successive number of processing of **Milky coloured pellets** (4)/3, (±SE).



Note 1: Successive processings performed in the past recycling cycles in Bangladesh.
Note 2: In-house successive processings had not been performed.

Figure 5.3: **MFR** vs. successive number of processing of **Dull-Brown Granules** (6)/6, (±SE).

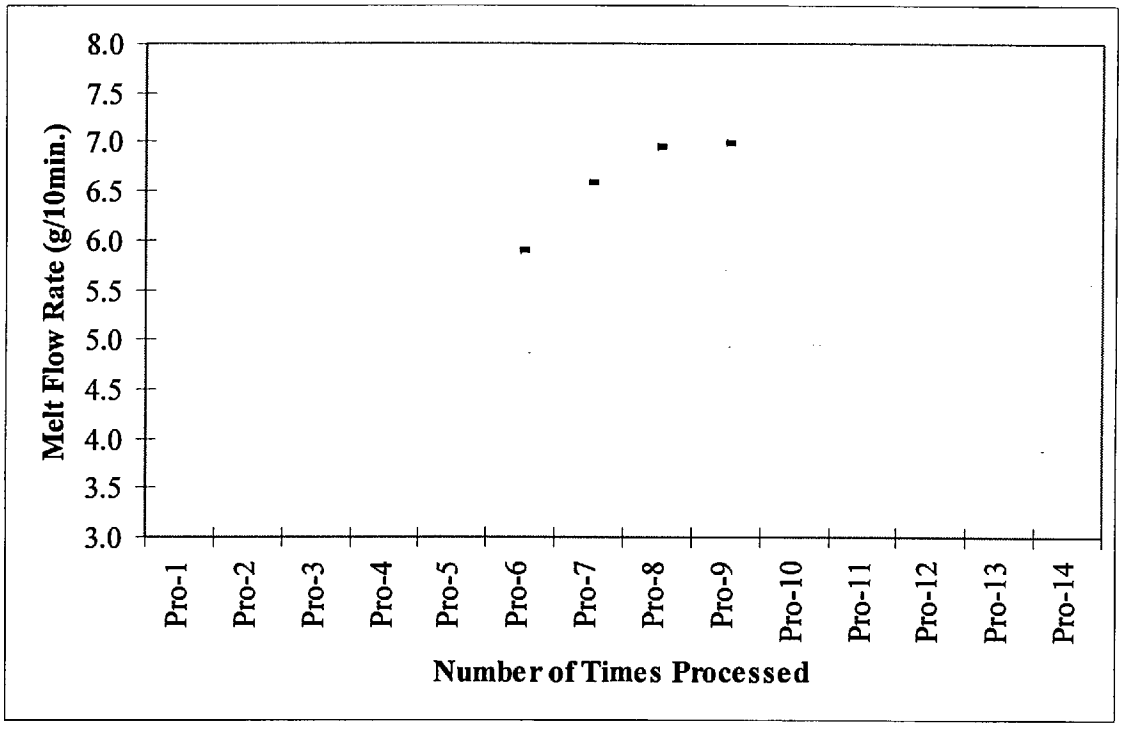


Figure 5.4: MFR vs. successive number of processing of the **Virgin Pellets-(1)/0.**

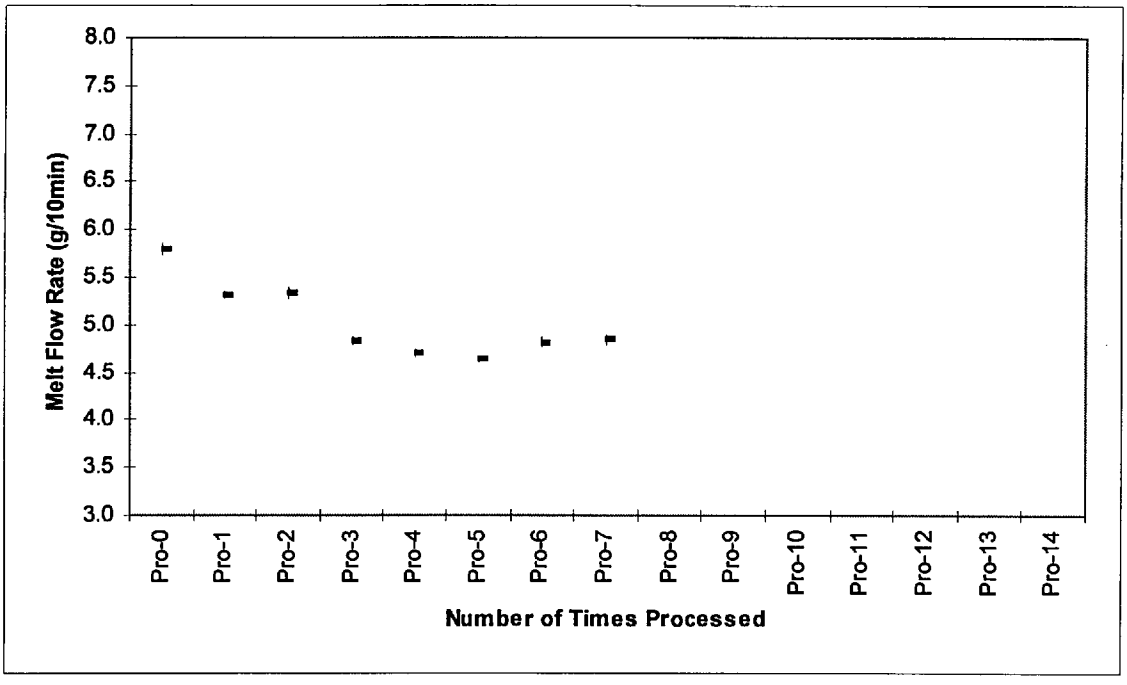
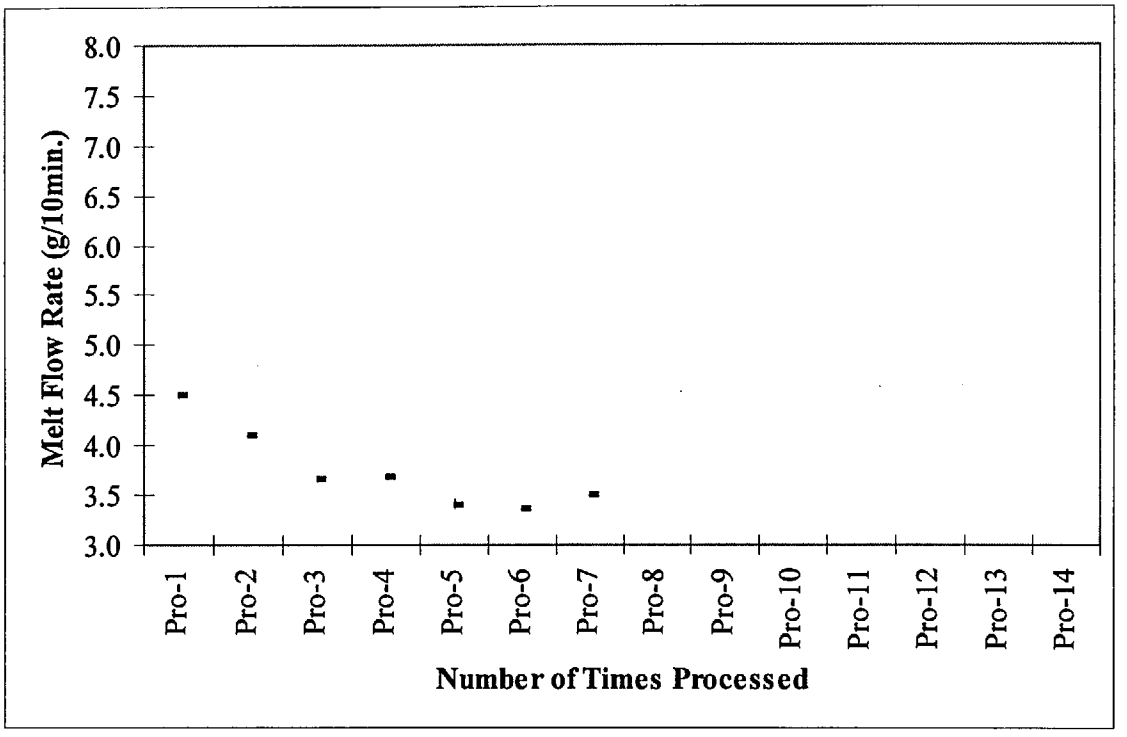


Figure 5.5: **MFR** vs. successive number of processing: **Translucent Flakes, Short Life,** (2A)/1, (±SE).



Except these four batches [(1)/0, (2A)/1, (4)/3 and (6)/6], the MFR values of all other batches of scraps remained the same, irrespective of the effect of successive extrusion-blow-mouldings (Table 5.1 and Appendix 5.1).

A comparison between the two batches of single grade translucent flakes - short life (2A)/1 and long life (2B)/1 shows that MFR values of the former materials are more or less the same for the latter materials but they behave differently following the number of processings (Figure 5.5 and Appendix 5.1.1). On the other hand, in Figure 5.6, the MFR values of the single washed translucent pellets (3A)/2 are different and remain at the higher level for all of the successive number of processings compared to its two derivatives which were cleaned by double washing, (3B)/2, and winnowing, (3C)/2. However, all these three materials [(3A)/2, (3B)/2 and (3C)/2] behaved similarly and experienced no change in their MFR values.

In Figure 5.7, there is an increase in MFR values for all of the scraps collected from Dhaka, Calcutta and Delhi, due to the effects of the closed-loop successive processing

within the present recycling system. There is an insignificant regional variation in their MFR for all of the process numbers involved.

Figure 5.6: A **comparison** among the **MFR** vs. successive number of processing of the **Translucent Pellets (3A)/2** with its **two derivatives (3B)/2 & (3C)/2.**

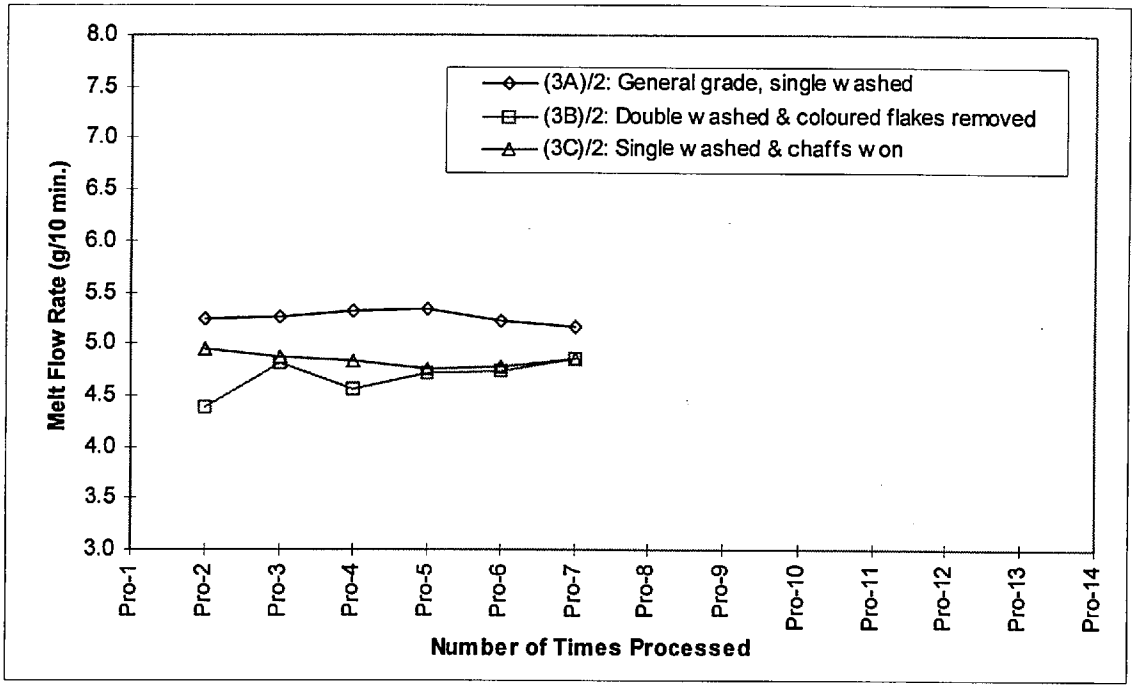
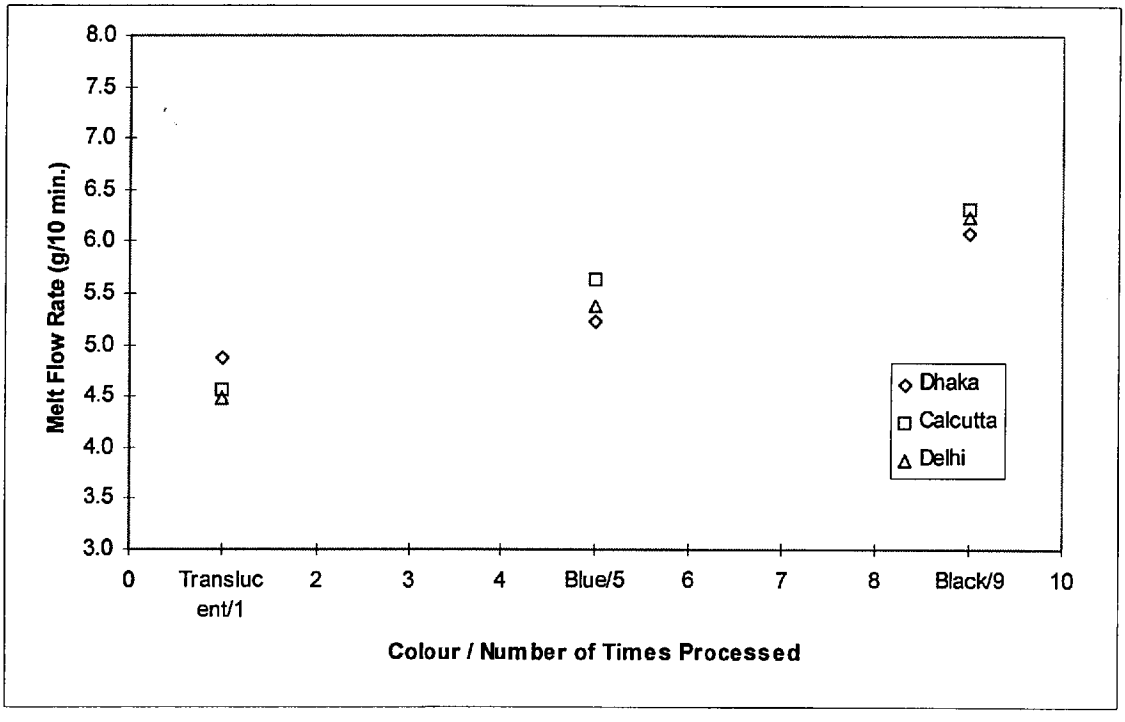


Figure 5.7: A **comparison** among the MFR values of the HDPE **General Scraps** collected from **Dhaka, Calcutta** and **Delhi.**



Overall, melt flow test results of HDPE general scraps indicate a small increase in their MFR with their increasing number of times processed previously under the existing recycling system. In the case of in-house successive extrusion-blow-mouldings of general scraps performed in Dhaka, similar increase in MFR is experienced by only two batches. However, an increase in their MFR from 4 g/10 min to 7 g/10 min after 13/14 times of processings is considered to be a small change (Dyson, 1997), although this increase is statistically significant.

A contradictory result, i.e. decrease in MFR, is observed in the case of in-house successive extrusion-blow-mouldings of the virgin pellets and once processed translucent flakes [(2A)/1] carried out under unknown processing conditions in Dhaka. These decreases in MFR are in accordance with the decrease after 6 number of successive extrusions performed under known processing conditions for the same virgin pellets in London (Figure 4.8 in Chapter 4).

5.4.2 Stress at Yield

The stress at yield results for the HDPE virgin material and the general scraps including their successively moulded materials are summarised in Table 5.2. As in Table 5.1, general directions of changes in their stress at yield values due to the in-house successive processing are also symbolised at the bottom of Table 5.2.

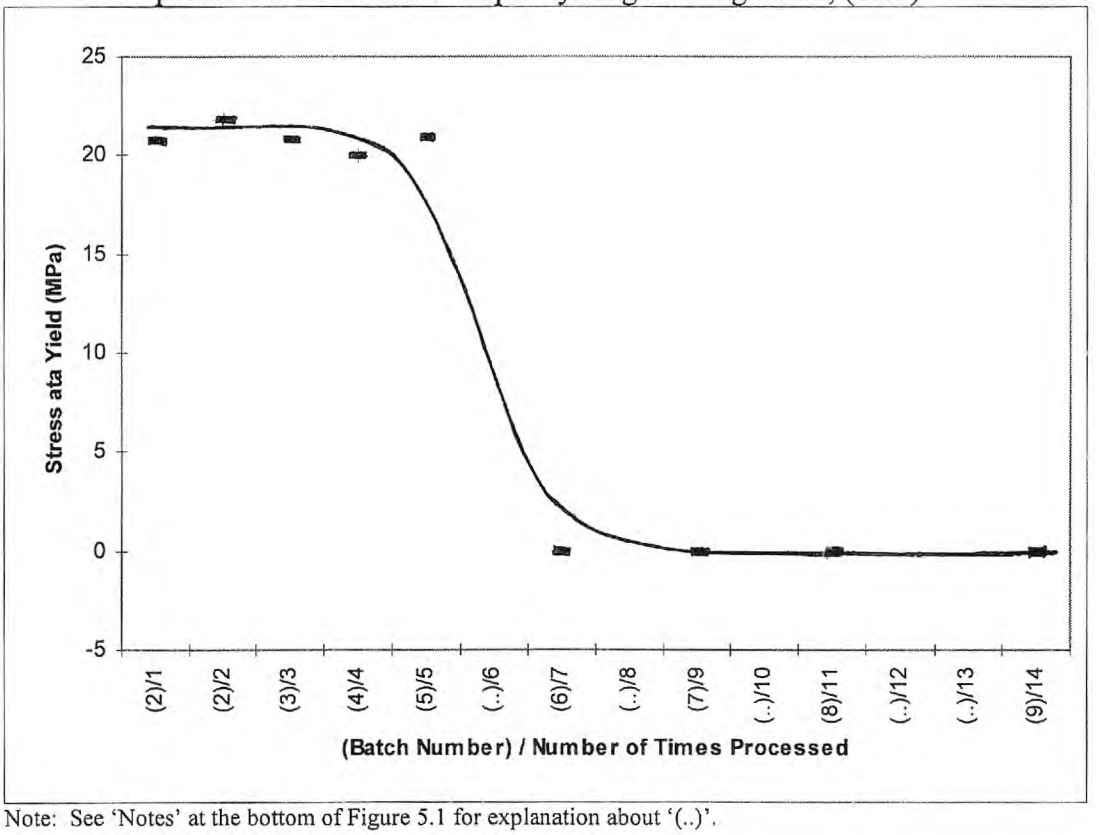
Along with the improvement in the MFR, the mechanical properties of the general scraps change accordingly to give an decrease in tensile strength. Figure 5.8 shows that a *catastrophic fall* in the stress at yield has been experienced by the general scraps processed more than 5-6 times under the closed-loop recycling system in Bangladesh. The reason for this fall can only be due to the increased brittleness of the materials, probably resulting from increasing contamination by a variety of unwanted materials and also from the uncontrolled melting processes employed in the country for recycling waste plastics.

Table 5.2: **STRESS AT YIELD** of the HDPE virgin and general scraps successively recycled and reprocessed in Dhaka, Bangladesh (In MPa).

Number of times processed within the factory premise ↓	**Description of the Feedstocks and Their Position According to the Number of Times Processed in the Real Environment**											
	Translucent virgin pellets observed : **Pro.– 0 Rcy.– 0**	Translucent flakes (of short life articles) : **Pro.– 1 Rcy.– 0**	Same waste stream of [2A] but of long life articles: **Pro.– 1 Rcy.– 0**	Translucent pellets (of short & long life articles & fractions): **Pro.– 2 Rcy.– 0**	3A, but washed twice & colour flakes removed before pelletising: **Pro.– 2 Rcy.– 0**	3A, but chaff won before pelletising: **Pro.– 2 Rcy.– 0**	Pellets (milky coloured): **Pro.–3 Rcy.– 0**	Granules (brown coloured): **Pro.–4/ 5 Rcy.– 1**	Granules (dull-brown coloured): **Pro.– 6/7 Rcy.– 2**	Granules (black coloured): **Pro.– 8/9 Rcy.– 3**	Granules (dull-black coloured): **Pro.–10/11 Rcy.– 4**	Granules (very dull-black colour: **Pro.–13/14 Rcy.– 5**
Batch No. →	(1)	(2A)	(2B)	(3A)	(3B)	(3C)	(4)	(5)	(6)	(7)	(8)	(9)
Pro. 0												
Pro. 1	25.5	20.79*										
Pro. 2	25.3	21.9	21.8									
Pro. 3	23.0	21.4	22.2	21.7	20.8	21.6						
Pro. 4	22.9	20.8	21.6	22.8	21.0	21.2	21.1					
Pro. 5	23.0	21.7	21.9	22.9	28.8	20.0	23.5	20.9				
Pro. 6	23.6	22.0	21.9	21.9	21.7	22.5	21.6	20.4				
Pro. 7	23.9	20.7	21.8	23.2	21.9	21.8	21.1	20.9	**Brittle**			
Pro. 8							21.9	21.5	20.1			
Pro. 9									20.2	**Brittle**		
Pro. 10										19.2		
Pro. 11											**Brittle**	
Pro. 12											18.5	
Pro. 13												
Pro. 14												**Brittle**
COMMENT	↓ or ?	S	S	S	S	S	S	S	S	?	?	?

Notes: ↓ - decreases; ↑ - increases; S - remains the same; ? - no comment in the cases where successive processings did not performed; *For the sample specimens cut off from a scrap jerry-cans.

Figure 5.8: **Stress at Yield** of the HDPE **General Scraps** versus number of processing performed in the close-loop recycling of Bangladesh, (±SE).



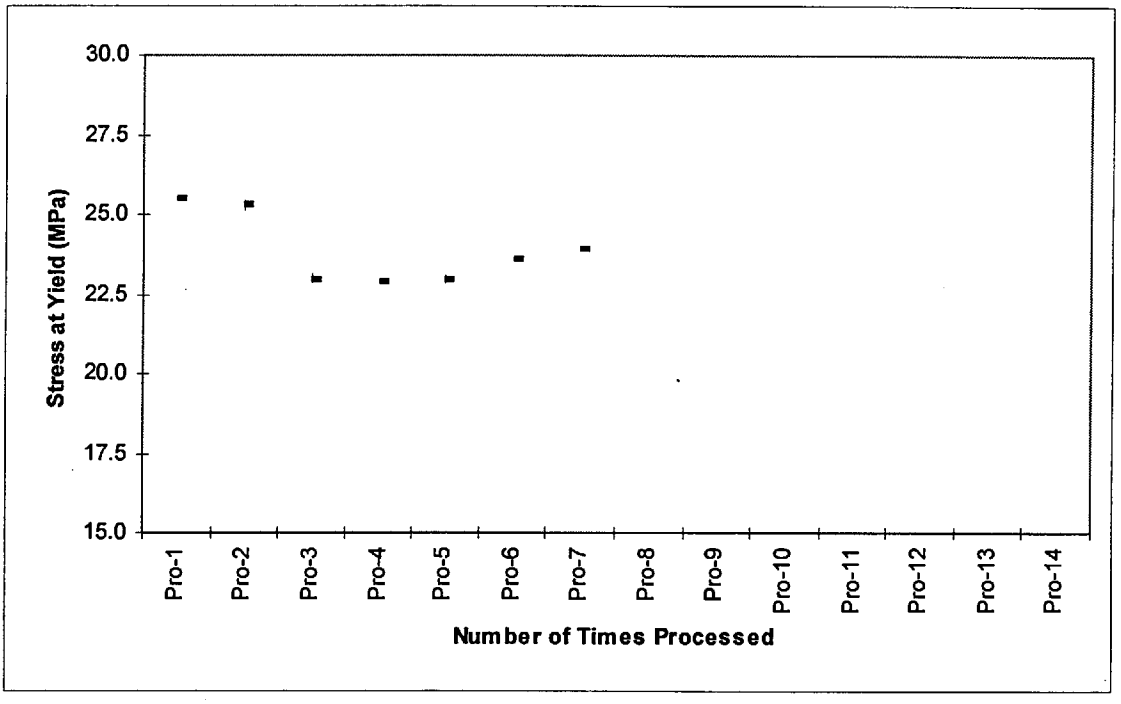
Note: See 'Notes' at the bottom of Figure 5.1 for explanation about '(..)'.

Photograph 5.1: Ductility of the 9 batches of materials from Dhaka against their number of times processed previously.



Figure 5.9 shows that a drop after twice reprocessing and then a slight improvement in the stress at yield of the virgin HDPE has occurred as a result of the effect of successive processing up to 7 times within the factory premises at Dhaka. However, with some exceptions, the stress at yield values against number of in-house processings remained fairly constant for all the scrap materials (Table 5.2 and Appendix 5.2). The stress at yield results for the dumb-bell specimens moulded from the scraps processed previously more than 6/7 times (batch no: 6-9 in Table 5.2) have shown their brittle nature (Photograph 5.1). However, in the next stages of successive mouldings, their brittle nature has disappeared, and all of them have yielded to some extent (Table 5.2).

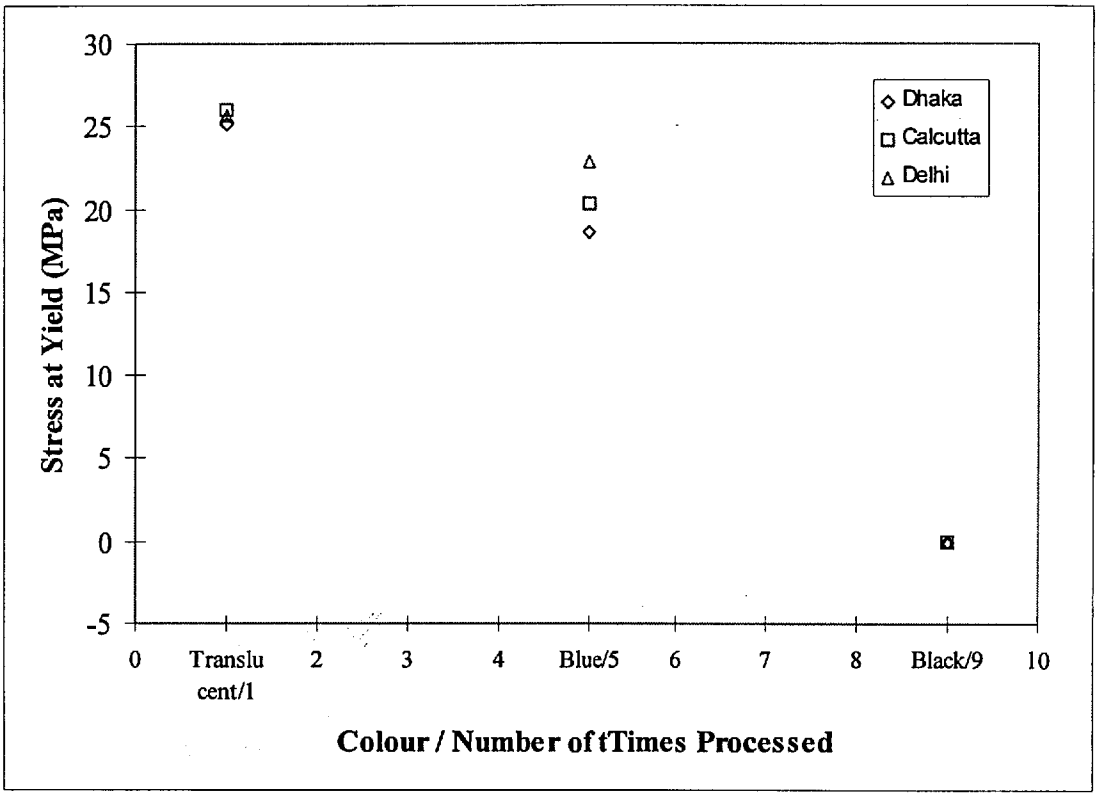
Figure 5.9: **Stress at Yield** of the HDPE **Virgin Pellets** vs. number of in-house successive processing performed at Dhaka (±SE).



A possible reason behind this initial brittleness is due to their degradation occurring, and higher proportion of impurities being incorporated cumulatively, during the past cycles of recycling. Contents of impurities increase cumulatively at every cycle. Extraneous particles act as obstructions between polymer molecules, which thus break dumb-bell specimens while in tension. However, where the materials are successively processed

within the factory premises, without entering into the using-discarding-recovering cycle where contamination occurs, their polymer parts do not receive any further impurities and regain ductility to some extent.

Figure 5.10: A **comparison** among the **Stress at Yield values** of the HDPE **General Scraps** collected from Dhaka, Calcutta and Delhi.



In the case of the HDPE general scraps collected from Calcutta and Delhi, these also experienced a similar fall in their stress at yield values as occurred for the general scraps from Dhaka (Figure 5.10). Interestingly, there is hardly any regional difference (insignificant) in the stress at yield values of the materials collected from the cities except the five times processed blue colour materials.

5.4.3 Stress at Break

Table 5.3 shows the stress at break properties of the HDPE general scraps as compared with the virgin pellets against their number of processing in the closed-loop recycling system and the number of in-house successive processings in Bangladesh. The major deterioration of properties in the reclaimed materials is represented by a significant decrease in their stress at break values. Figure 5.11 shows a fall of 7-8 MPa in the stress at break property of the general scraps around 4 times of processings, and then further decrease with increasing processing numbers.

Similarly decrease in stress at break, but to a lesser extent, occurs upon in-house extrusion-blow-moulding for some of the materials, viz. (i) virgin pellets, (1)/0, (ii) translucent pellets, mixed grade, (3A)/2, (iii) translucent pellets but chaff won (3C)/2, and (iv) dull-brown granules, (6)/6. Their stress at break vs. number of in-house successive processings are shown in Figures 5.12, 5.13 and 5.14.

Since this decrease in break values has occurred not only in the case of general scraps but also for the virgin pellets which are clean, it may provide evidence that variation in inherent nature of degradation of a material and its reprocessing parameters (such as temperature, pressure and retention time) play greater effects than the level of impurity contents alone. As a result no fruitful improvement in stress at break is achieved by double washing or winnowing the scrap materials, which is shown in Figure 5.13. The main cause of the decrease of stress at break may be attributed to the apparent break down of the existing gel fraction due to effects of intensive shearing of successive recycling using the locally produced traditional single screw moulding machines.

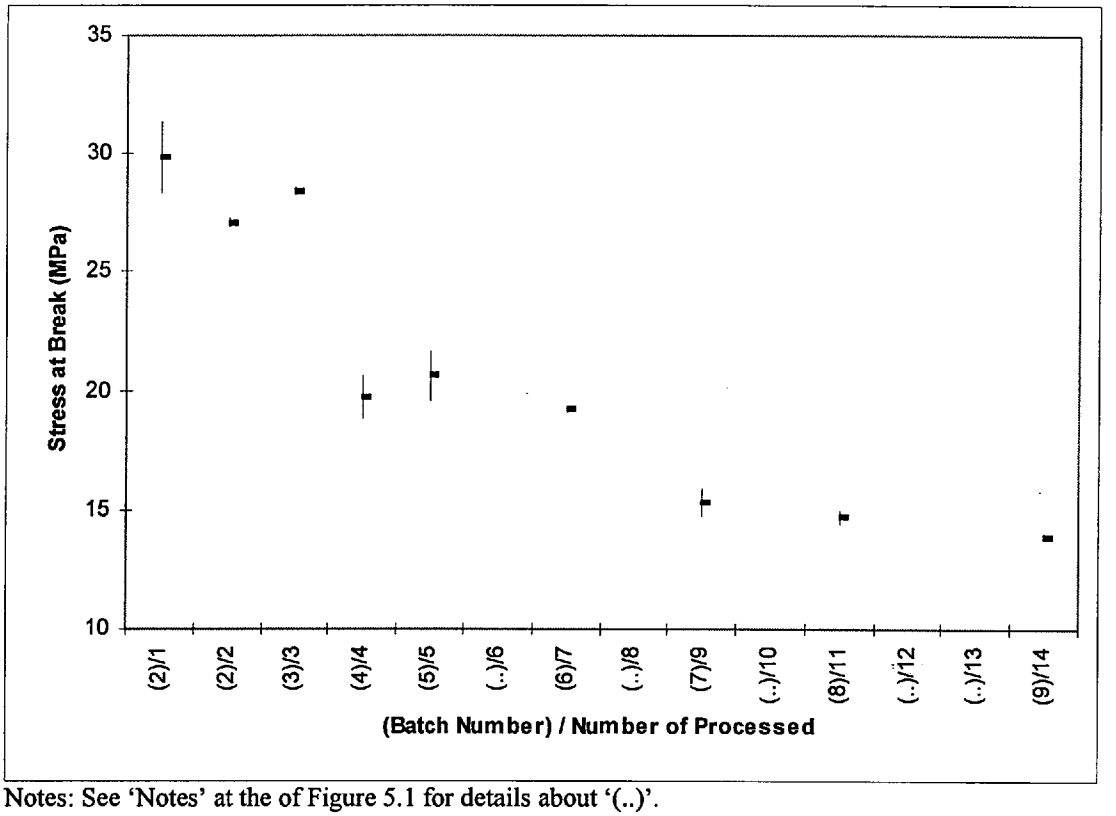
All other scrap materials remained the same in their stress at break values, irrespective of the effect of in-house successive processing, except the double washed translucent flakes, (3B)/2 and brown granules, (5)/4, which experienced a slight improvement in their stress at break (Appendix 5.3).

Table 5.3: **STRESS AT BREAK** of the HDPE **virgin** and **general scraps** successively recycled and reprocessed in Dhaka, Bangladesh (In MPa).

Number of times processed within the factory premise ↓	**Description of the Feedstocks and Their Position According to the Number of Times Processed in the Real Environment**											
	Translucent virgin pellets observed : **Pro.– 0 Rcy.– 0**	Translucent flakes (of short life articles) : **Pro.– 1 Rcy.– 0**	Same waste stream of [2A] but of long life articles: **Pro.– 1 Rcy.– 0**	Translucent pellets (of short & long life articles & fractions): **Pro.– 2 Rcy.– 0**	3A, but washed twice & colour flakes removed before pelletising: **Pro.– 2 Rcy.– 0**	3A, but chaff won before pelletising: **Pro.– 2 Rcy.– 0**	Pellets (milky coloured): **Pro.–3 Rcy.– 0**	Granules (brown coloured): **Pro.–4/ 5 Rcy.– 1**	Granules (dull-brown coloured): **Pro.– 6/7 Rcy.– 2**	Granules (black coloured): **Pro.– 8/9 Rcy.– 3**	Granules (dull-black coloured): **Pro.–10/11 Rcy.– 4**	Granules (very dull-black colour: **Pro.–13/14 Rcy.– 5**
Batch No. →	(1)	(2A)	(2B)	(3A)	(3B)	(3C)	(4)	(5)	(6)	(7)	(8)	(9)
Pro. 0												
Pro. 1	**30.7**	29.84*										
Pro. 2	27.4	**27.1**	**26.5**									
Pro. 3	26.9	29.9	27.3	**28.4**	**24.3**	**27.8**						
Pro. 4	23.7	22.7	23.0	26.9	24.7	27.1	**21.9**					
Pro. 5	18.4	27.7	25.5	26.1	24.7	22.2	15.8	**20.6**				
Pro. 6	19.6	23.4	28.3	24.0	28.9	21.1	20.1	20.5				
Pro. 7	20.6	28.8	28.5	21.1	25.5	20.3	18.4	21.7	**19.2**			
Pro. 8							17.4	24.4	18.2			
Pro. 9									13.8	**15.3**		
Pro. 10										14.4		
Pro. 11											**14.7**	
Pro. 12												
Pro. 13												
Pro. 14												**13.9**
COMMENT	↓	S	S	↓	S	↓	S	S	↓	S	?	?

Notes: ↓ - decreases; ↑ - increases; S - remains the same; ? - no comment in the cases where successive processings were not performed; *For the sample specimens cut off from scrap jerry-cans.

Figure 5.11: **Stress at Break** vs. number of times processed: **HDPE General Scraps** recovered from the waste streams of Bangladesh (±SE).



Notes: See 'Notes' at the of Figure 5.1 for details about '(..)'.

Figure 5.12: **Stress at Break** of the HDPE **Virgin Pellets, (1)/0,** vs. number of in-house successive processing performed at Dhaka (±SE).

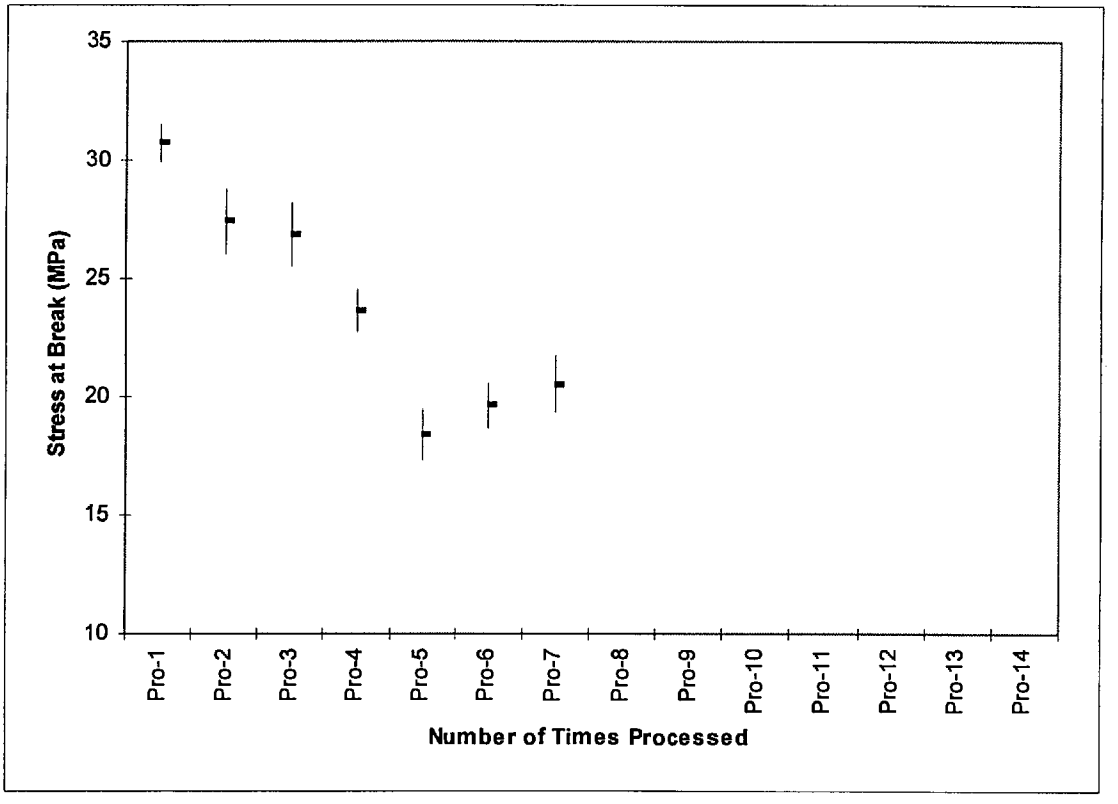


Figure 5.13: A **comparison** among the **Stress at Break** vs. successive numbers of processing of the **Mixed Grade Translucent Pellets (3A)/2** with its **two derivatives (3B)/2 & (3C)/2.**

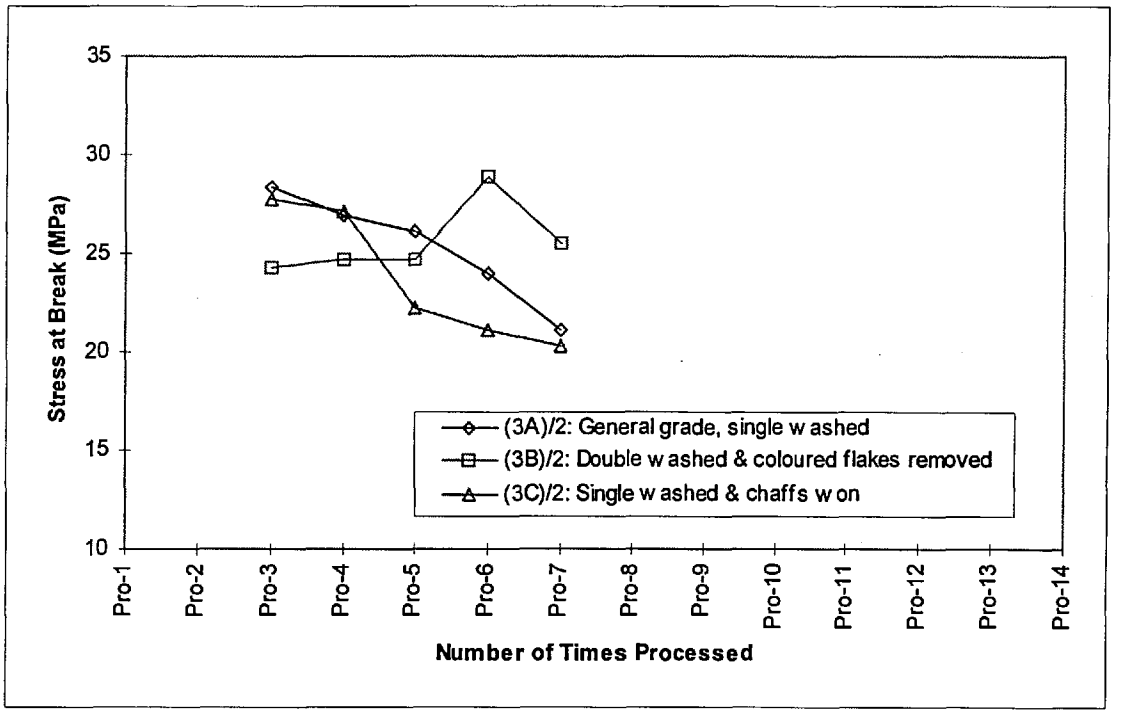


Figure 5.14: **Stress at Break** of the HDPE **Dull-brown Granules, (6)/6,** vs. successive number of processings performed at Dhaka (±SE).

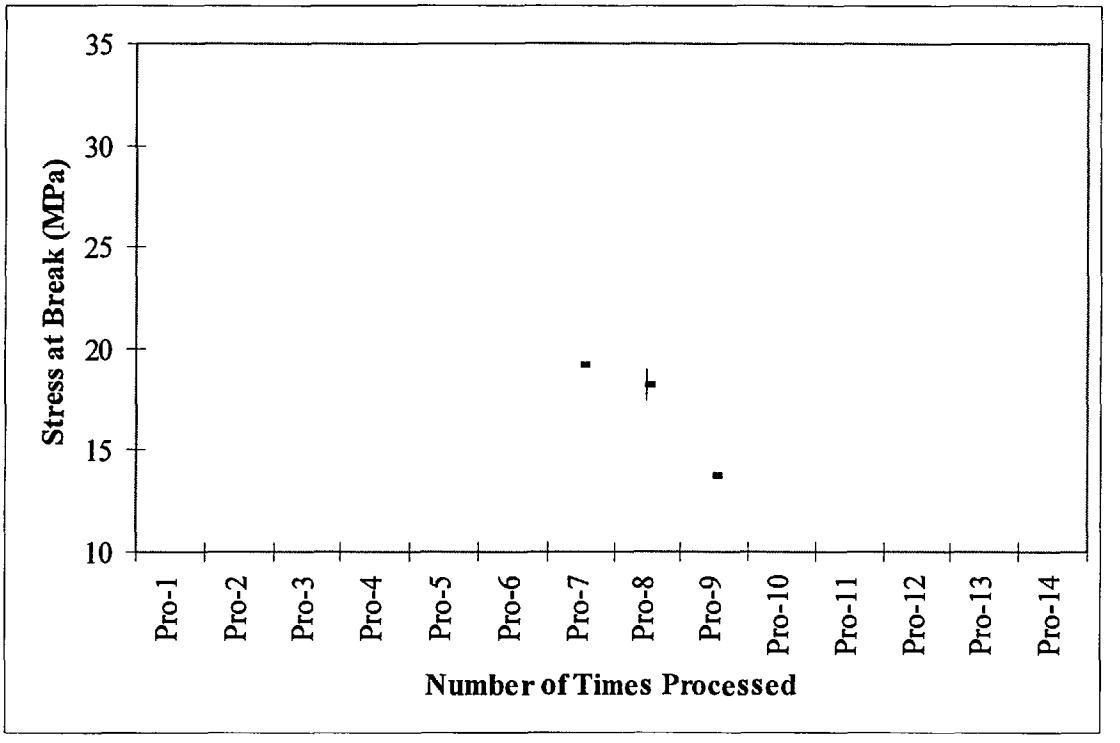
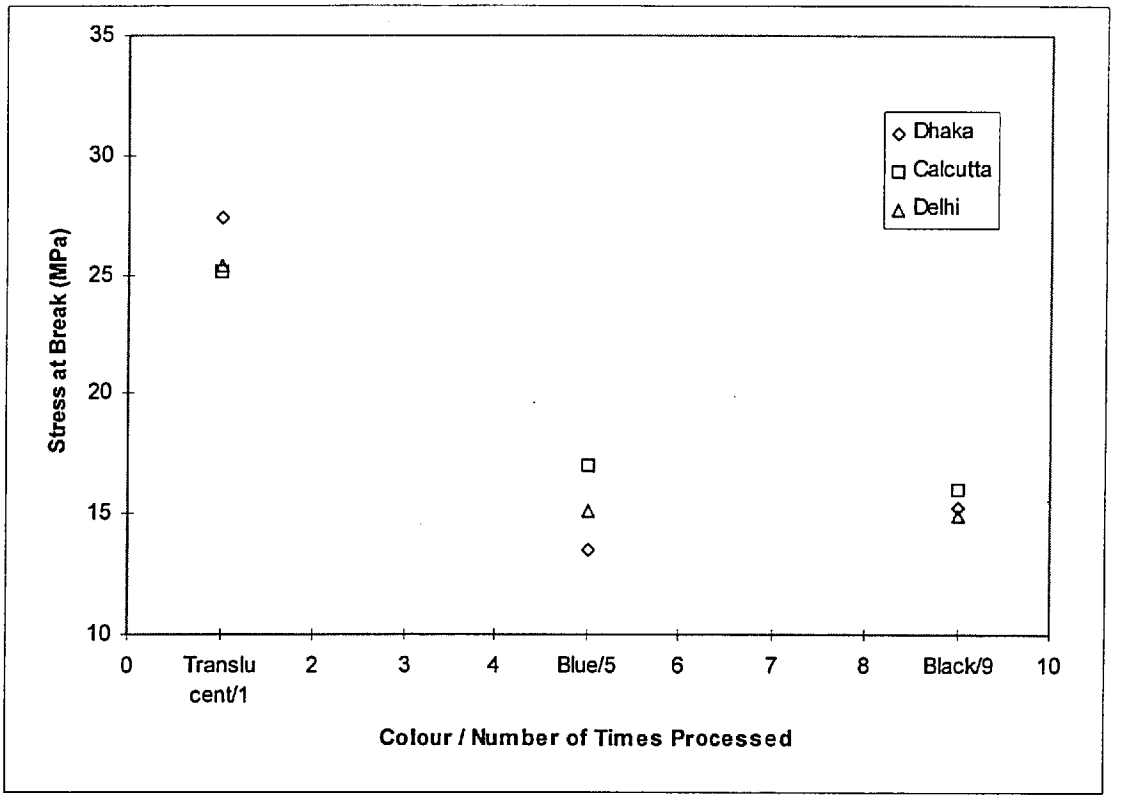


Figure 5.15: A **comparison** among the **Stress at Break** values of the HDPE **General Scraps** collected from **Dhaka, Calcutta** and **Delhi.**



A decrease in stress at break with an insignificant regional variation has also occurred for the HDPE materials collected from Dhaka, Calcutta and Delhi (Figure 5.15).

5.4.4 Strain at Break

Figure 5.16 illustrates stress vs. strain property of the HDPE virgin and general scraps previously injection-blow-moulded several times in Bangladesh. Table 5.4 summarises the results of strain at break against number of in-house processings of these materials. In accordance with the decrease in stress at yield and stress at break phenomena of the general scraps, Figure 5.17 and Photograph 5.1 (in sub-section 5.4.2) indicate a *drastic fall* in their strain at break values at around 6/7th numbers of processing.

Figure 5.16: **Stress-strain curves** of HDPE **Virgin** (imported) and **General Scraps** previously injection-blow-moulded several times in Bangladesh.

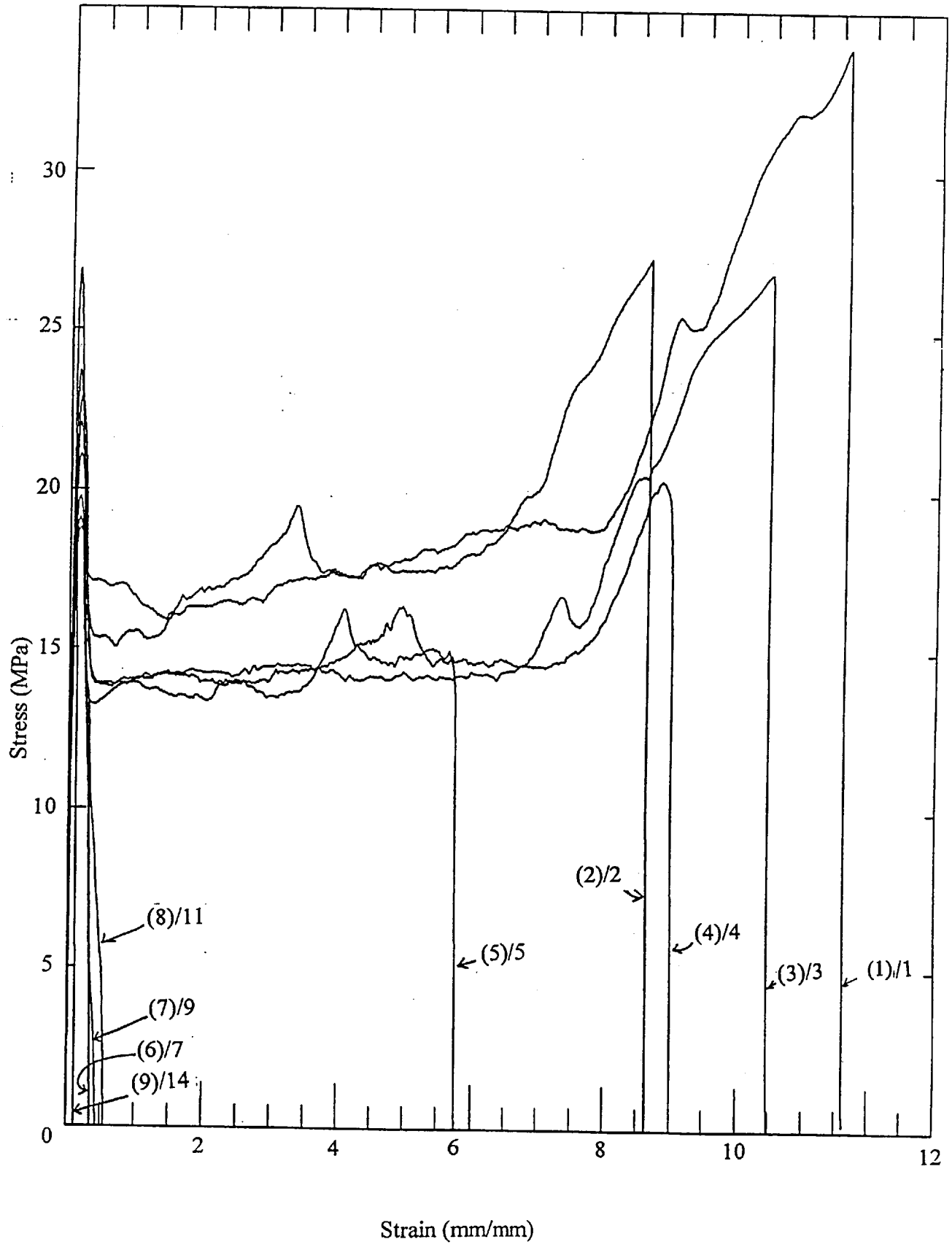
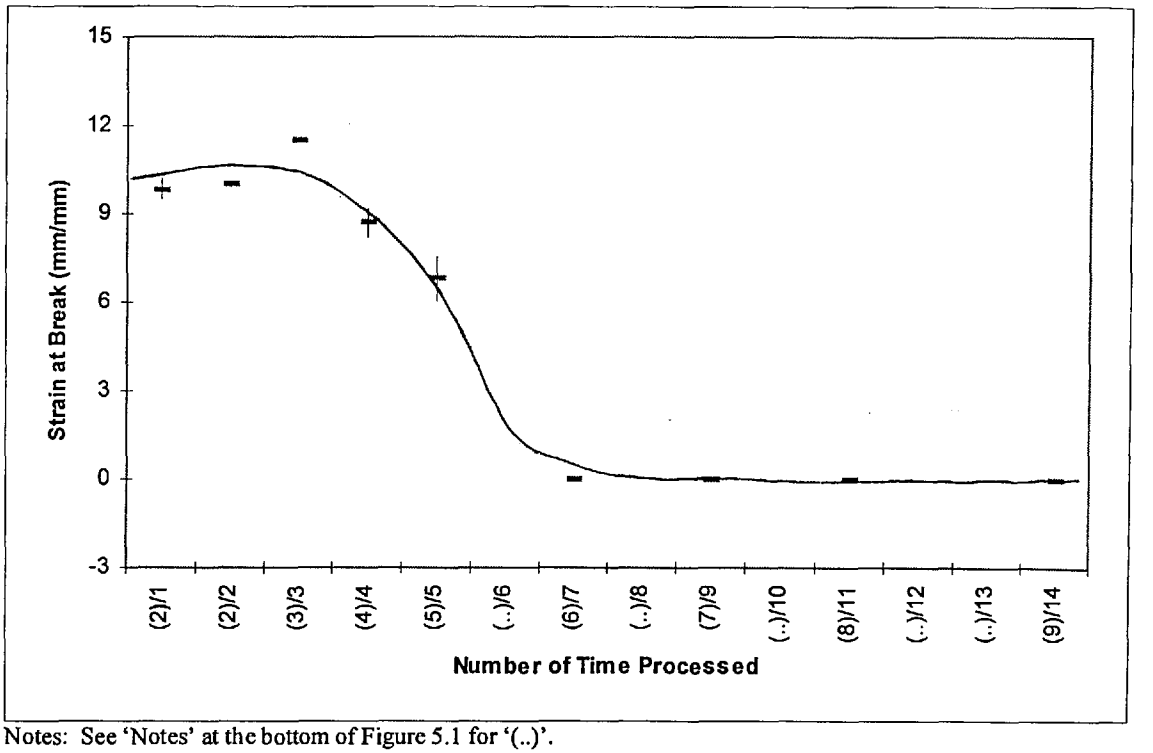


Table 5.4: **STRAIN AT BREAK** of the HDPE **virgin** and **general scraps** successively recycled and reprocessed in Dhaka, Bangladesh (mm/mm).

Number of times processed within the factory premise ↓	**Description of the Feedstocks and Their Position According to the Number of Times Processed in the Real Environment**											
	Translucent virgin pellets observed : **Pro.– 0 Rcy.– 0**	Translucent flakes (of short life articles) : **Pro.– 1 Rcy.– 0**	Same waste stream of [2A] but of long life articles: **Pro.– 1 Rcy.– 0**	Translucent pellets (of short & long life articles & fractions): **Pro.– 2 Rcy.– 0**	3A, but washed twice & colour flakes removed before pelletising: **Pro.– 2 Rcy.– 0**	3A, but chaff won before pelletising: **Pro.– 2 Rcy.– 0**	Pellets (milky coloured): **Pro.–3 Rcy.– 0**	Granules (brown coloured): **Pro.–4/ 5 Rcy.– 1**	Granules (dull-brown coloured): **Pro.– 6/7 Rcy.– 2**	Granules (black coloured): **Pro.– 8/9 Rcy.– 3**	Granules (dull-black coloured): **Pro.–10/11 Rcy.– 4**	Granules (very dull-black colour: **Pro.–13/14 Rcy.– 5**
Batch No. →	(1)	(2A)	(2B)	(3A)	(3B)	(3C)	(4)	(5)	(6)	(7)	(8)	(9)
Pro. 0												
Pro. 1	10.8	9.85*										
Pro. 2	9.2	10.0	9.4									
Pro. 3	9.5	10.5	9.2	11.5	8.1	10.1						
Pro. 4	7.6	8.3	8.2	11.2	7.7	9.8	8.7					
Pro. 5	5.0	9.9	8.8	10.2	9.1	7.9	3.2	6.8				
Pro. 6	4.8	8.6	9.8	8.2	10.3	6.9	7.2	6.1				
Pro. 7	5.1	10.2	9.7	7.8	10.1	5.9	7.1	7.5	**Brittle**			
Pro. 8							7.1	8.9	7.2			
Pro. 9									2.7	**Brittle**		
Pro. 10										3.2		
Pro. 11											**Brittle**	
Pro. 12												
Pro. 13												
Pro. 14												**Brittle**
COMMENT	↓	S	S	↓	S	↓	S	S	↓	?	?	?

Notes: ↓ - decreases; ↑ - increases; S - remains the same; ? - no comment in the cases where successive processings were not performed; *For the sample specimens cut off from scrap jerry-cans.

Figure 5.17: **Strain at Break** vs. number of times processed: **HDPE General Scraps** recovered from the waste streams of Bangladesh (±SE).



Notes: See 'Notes' at the bottom of Figure 5.1 for '(..)'.

A *severe change (decrease)* in strain at break properties has also taken place in the case of virgin pellets, (1)/0, following the effects of successive processings. Stress-strain curves (Figure 5.18) and distribution of error bars (Figures 5.19) of these successively processed virgin pellets illustrate this decrease in their strain at break values. It is also reasonable to assume that general scraps and virgin HDPE behave similarly (Figures 5.17 and 5.19).

This indicates that mechanico-thermal effects resulting from successive reprocessings under unknown and inconsistent processing conditions (i.e. fluctuation in heating, retention time, speed, level of possible contaminants, and level of operator's skills) are the major factors in degrading polymer properties. These effects are likely to be more deleterious when extraneous substances are present in the feedstocks.

Similarly, a reduction in strain at break also observed for twice processed translucent pellets, (3A)/2 and (3C)/2, as a result of in-house successive processings (Figures 5.20).

Figure 5.18: **Stress-strain curves** of HDPE **Virgin** successively injection-blow-moulded up to 7 times in Dhaka.

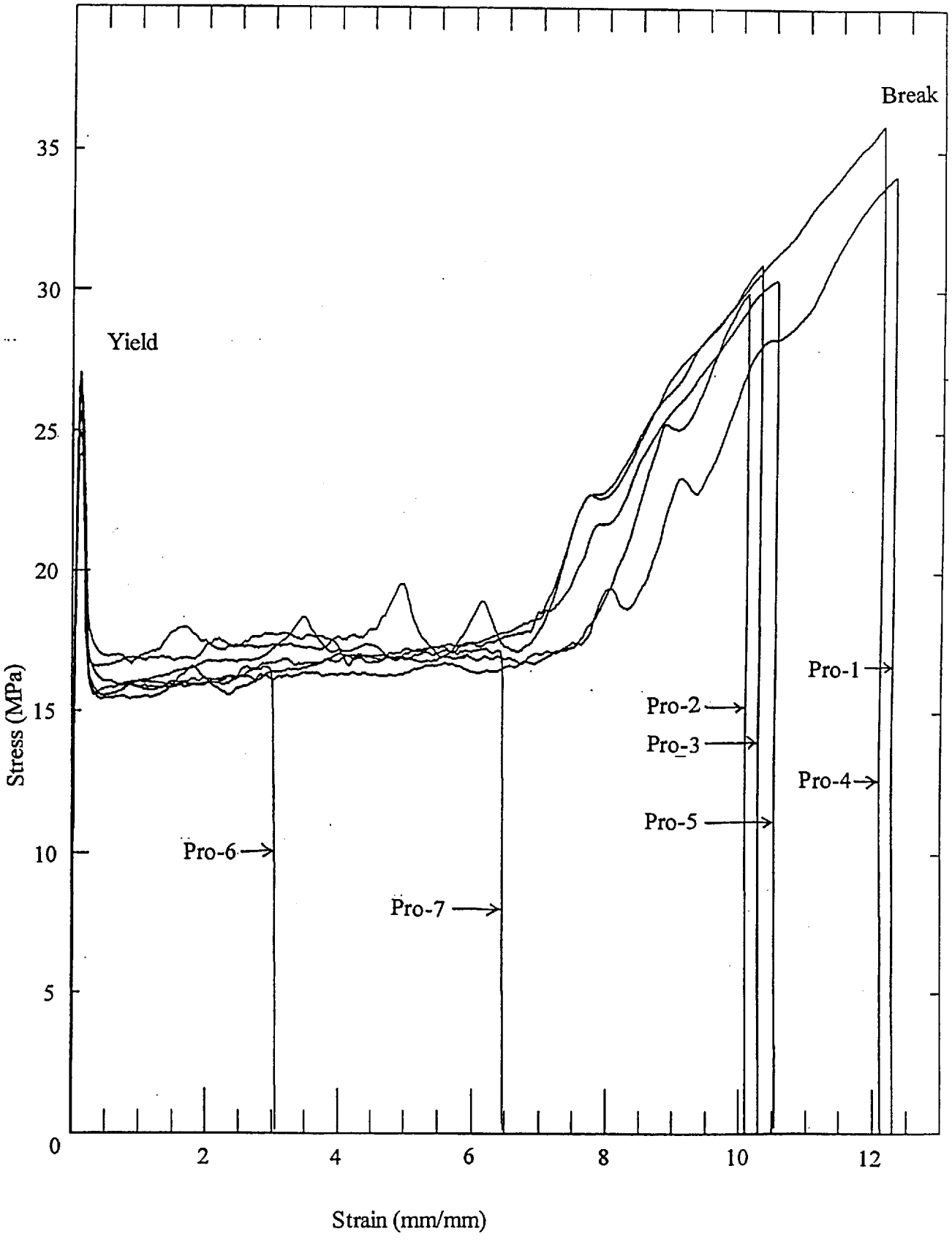


Figure 5.19: **Strain at Break** of the HDPE **Virgin Pellets, (1)/0,** vs. number of in-house successive processings performed at Dhaka (±SE).

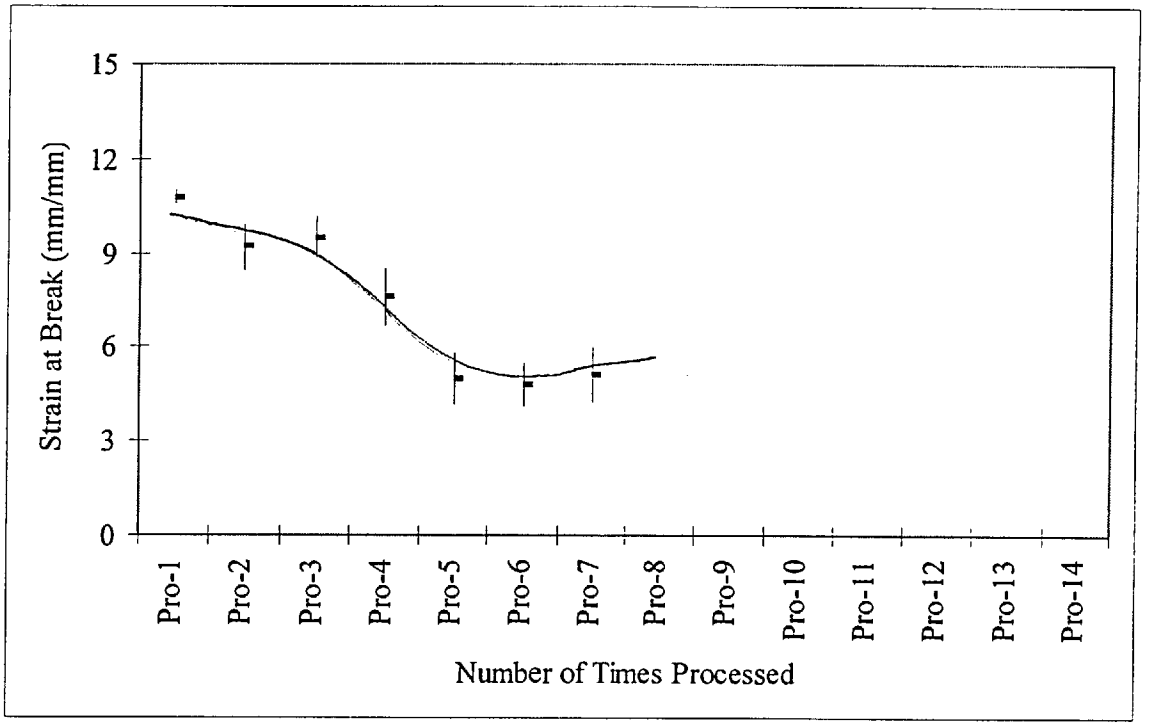


Figure 5.20: A **comparison** among the **Strain at Break** vs. successive number of processing of the **Mixed Grade Translucent Pellets (3A)/2** with its **two derivatives (3B)/2 & (3C)/2.**

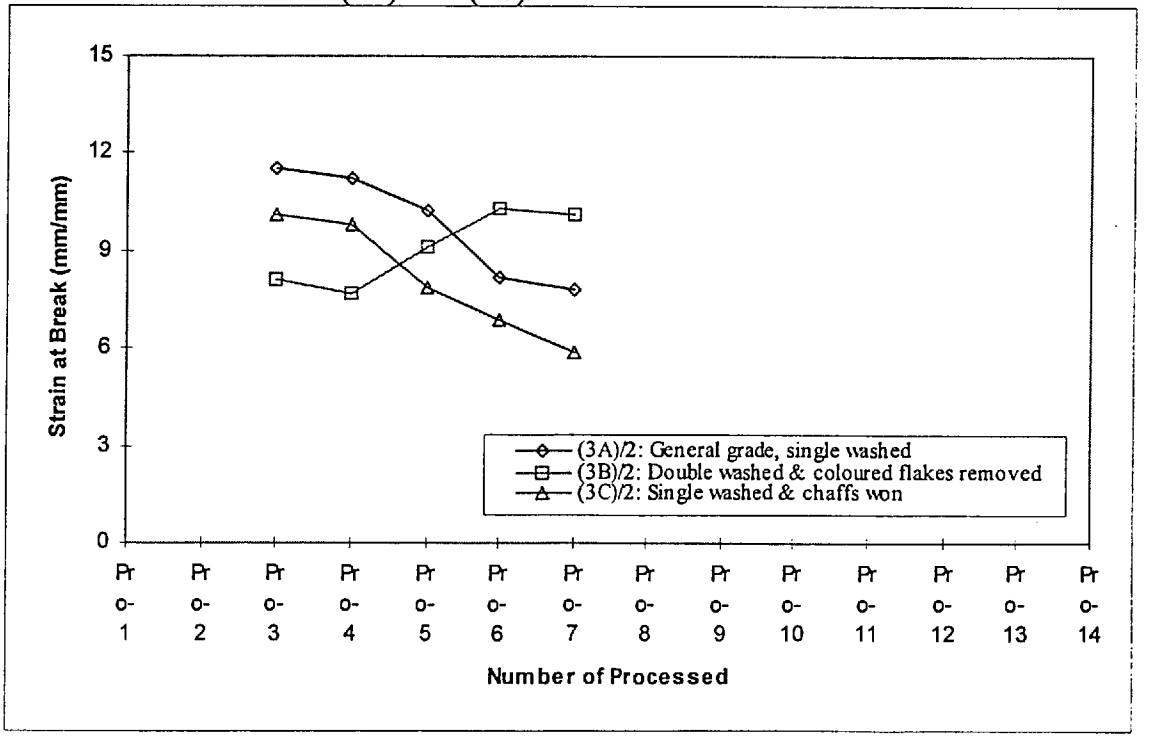
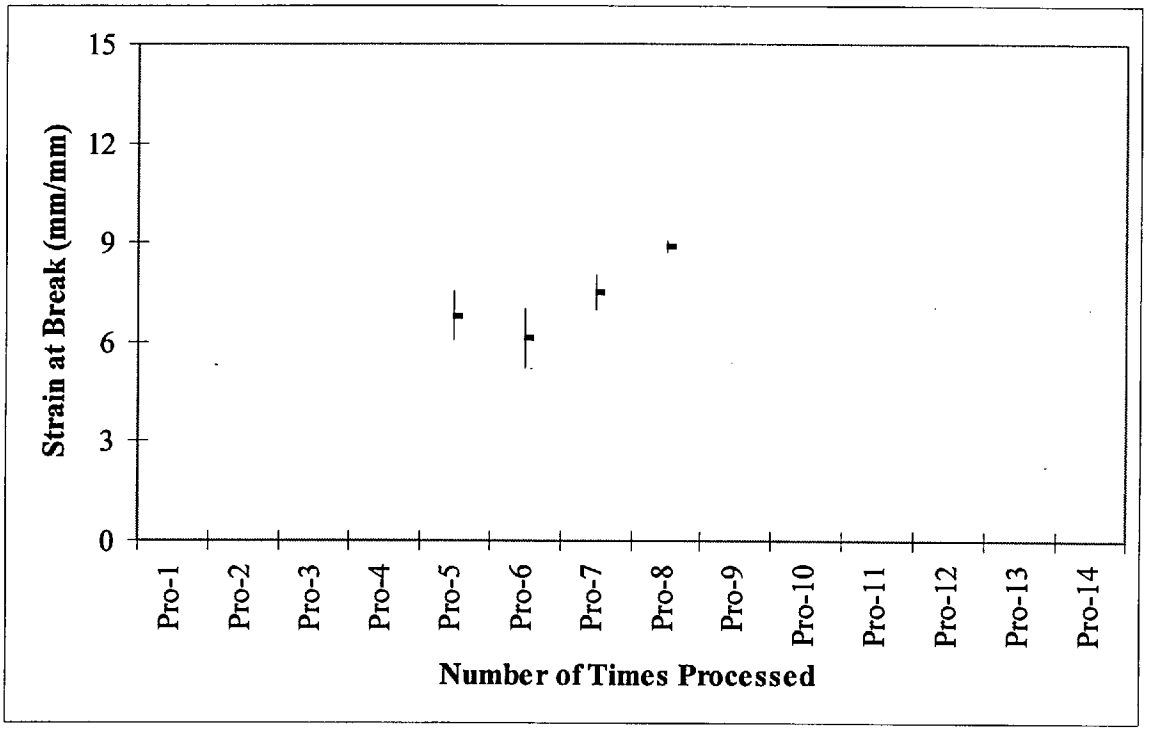


Figure 5.21: **Strain at Break** of the HDPE **Brown Granules, (5)/4,** vs. successive number of processings performed at Dhaka (±SE).



In contrast, successive in-house moulding has also resulted a slight improvement in strain at break for some of the general scraps such as translucent double washed pellets (3A)/2, brown granules, (5)/4, dull-brown granules, (6)/6, and black granules, (7)/8, as shown in Figures 5.20, 5.21, 5.22 and 5.23, respectively. It is important to note that, in Figure 5.13 and 5.20, improvement or at least maintenance of stress at break and strain at break properties of twice processed translucent pellets, (3A)/2, can be achieved by enhancing existing plastics washing and cleaning efficiency.

Insignificant effects of successive processings on the strain at break properties of the other scrap materials are shown in Table 5.4 and Appendix 5.4. In the case of black granules, improvement even from brittleness to ductileness was observed.

Figure 5.22: **Strain at Break** of the HDPE **Dull-brown Granules, (6)/6,** vs. successive number of processings performed at Dhaka (±SE).

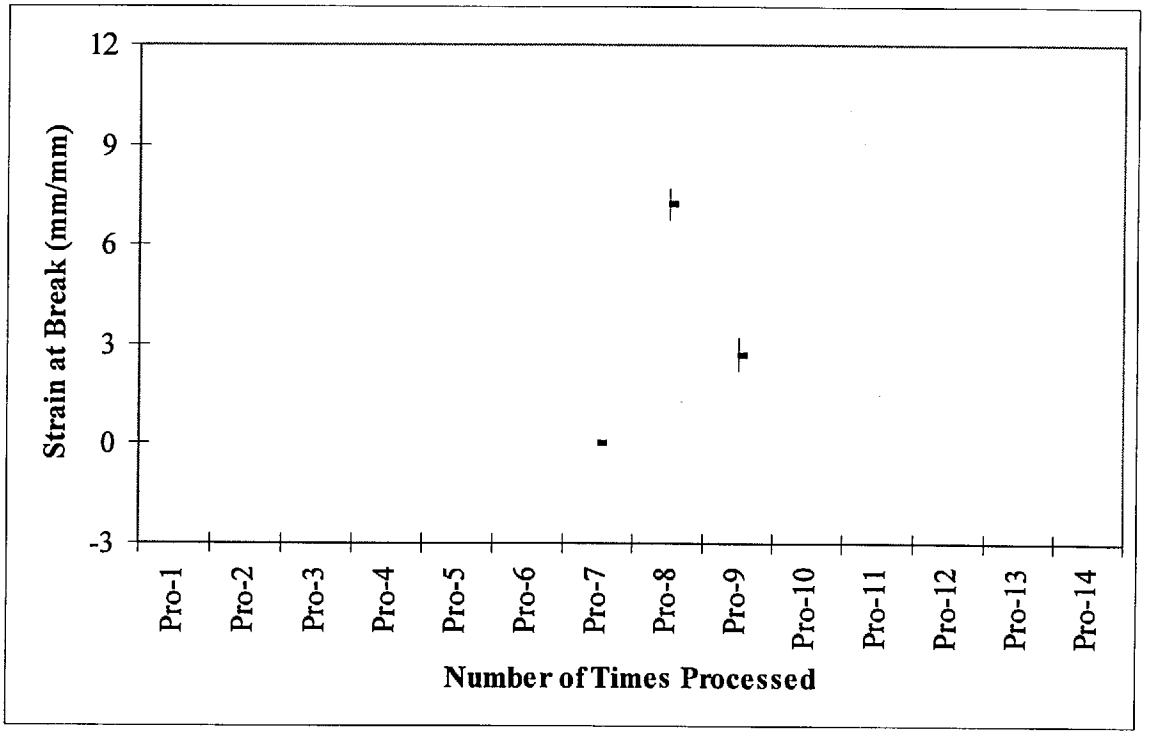


Figure 5.23: **Strain at Break** values of the HDPE **Black, (7), Dull Black, (8), and Very Dull Black, (9),** scraps collected from Dhaka city (±SE).

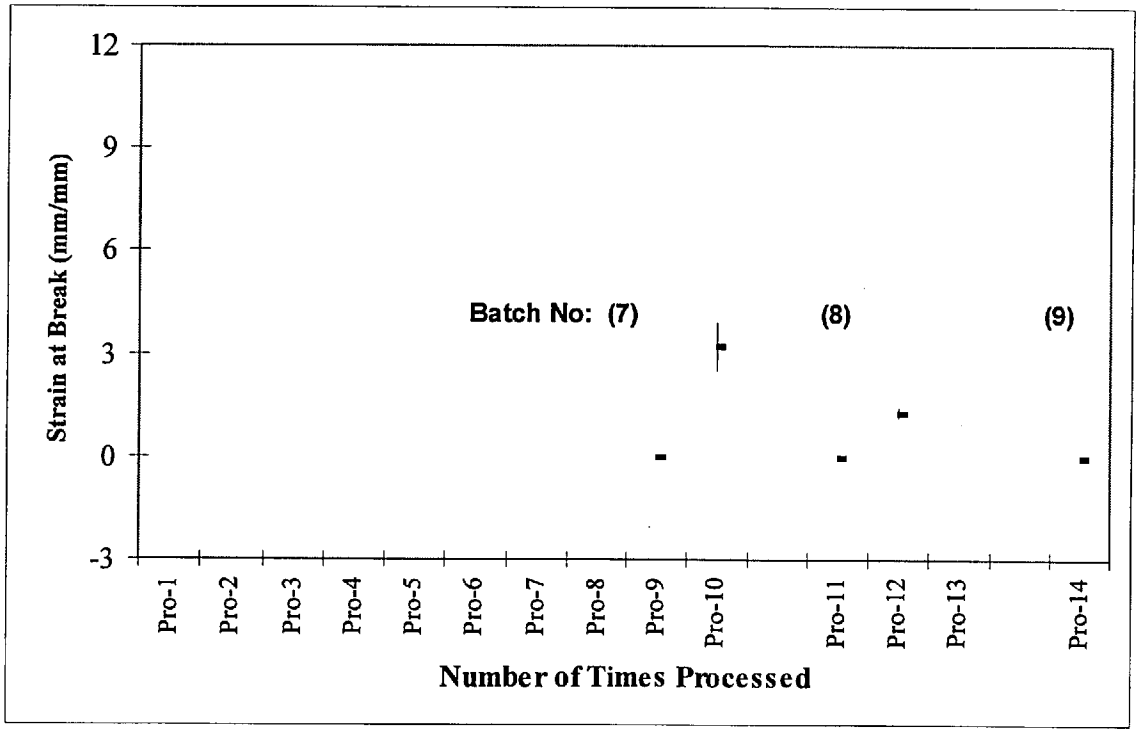


Figure 5.24: A comparison among the **Strain at Break** values of the HDPE **General Scraps** collected from Dhaka, Calcutta and Delhi.

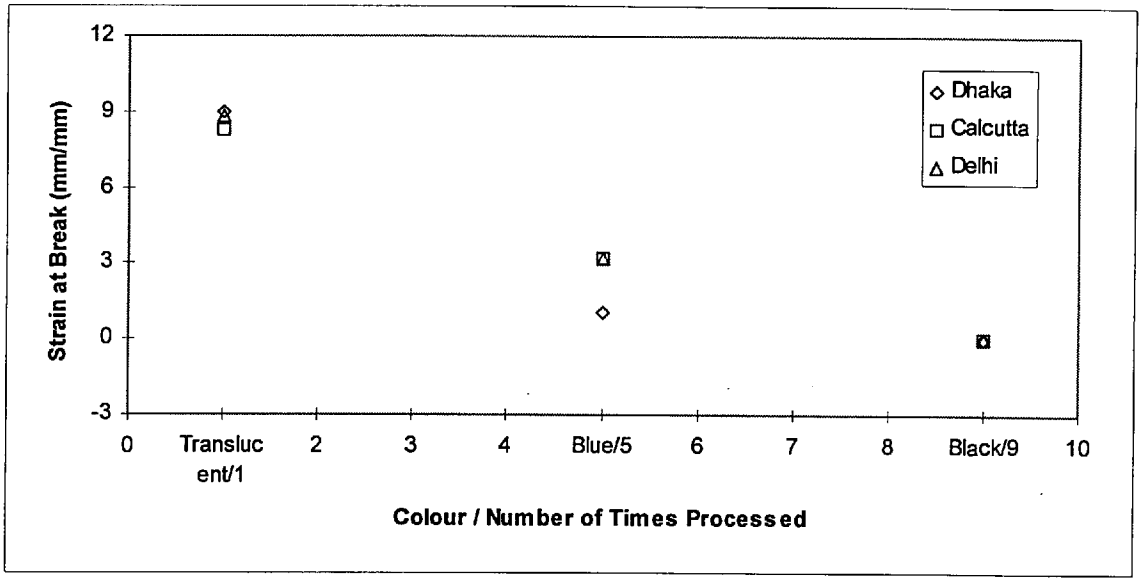


Figure 5.24 shows a significant decrease in strain at break values of the scraps plastics collected from Dhaka, Calcutta and Delhi. The results for the materials from Dhaka are very close to the corresponding results obtained for the materials from the other two cities. It means there is hardly any regional difference in their decreasing strain at break properties.

5.4.5 Impact Resistance

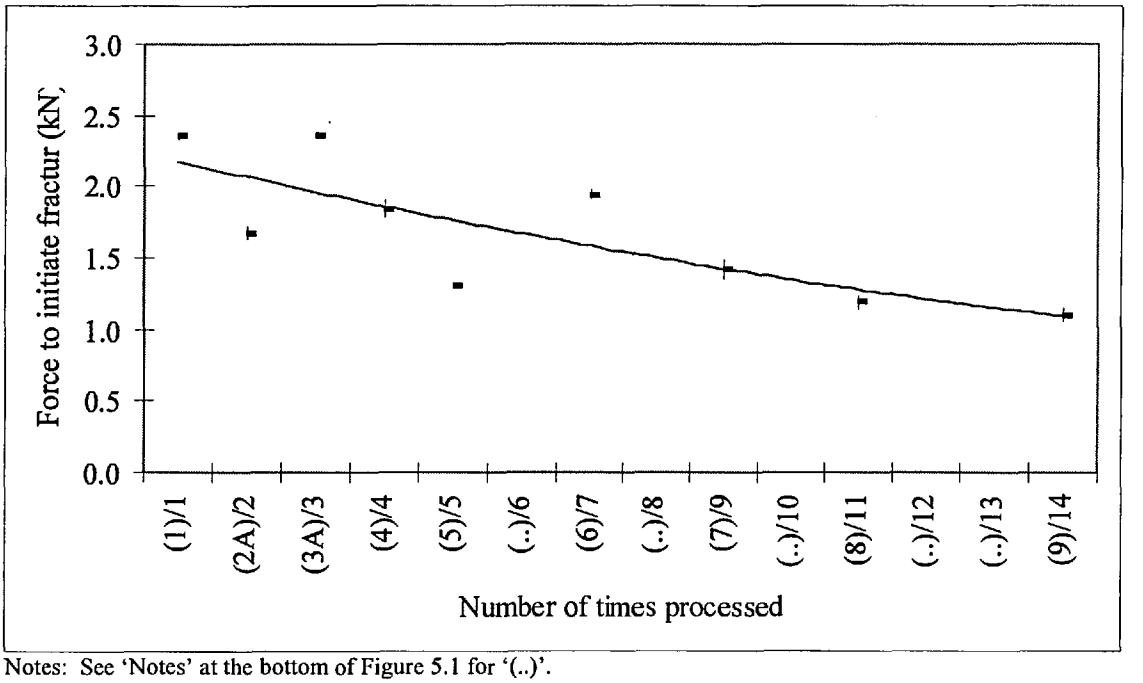
In addition to the MFR and tensile strength test results of the HDPE virgin and general scraps described above, their impact strength performance was tested by striking with a free-falling dart (see subsections 5.3.3 of this chapter and 4.3.4 of Chapter 4), in order to achieve a better understanding about the nature of their property changes with successive numbers of processings (Table 5.5). 'Force required to initiate fracture' (F) on the plaque specimens decreases for the material processed with the higher number of times (Figure 5.25).

Table 5.5: Impact parameters vs. number of processing for HDPE virgin and general scraps from Dhaka.

Notations of the materials	Force required to initiate fracture, F	Deflection or distance to fracture, d	Energy required for deflection to fracture, E1	Total energy required for fracture and crack propagation E2	Energy required for crack propagation, E2 - E1
(BN)/NTP	(kN)	(mm)	(J)	(J)	(J)
(1)/0	2.35	11.98	12.68	18.58	5.90
(2A)/1	1.67	8.96	6.09	9.46	3.37
(2B)/1	1.60	8.88	5.74	10.45	4.72
(3A)/2	2.36	10.79	10.88	15.66	4.78
(3B)/2	1.67	8.48	5.78	10.81	5.04
(3C)/2	2.39	10.76	11.14	15.68	4.53
(4)/3	1.84	9.98	7.70	12.62	4.92
(5)/4	1.31	7.90	4.13	8.51	4.38
(6)/6	1.94	9.83	8.12	12.18	4.06
(7)/8	1.42	8.48	4.99	9.42	4.43
(8)/10	1.19	7.28	3.33	8.26	4.92
(9)/13	1.10	7.63	3.31	8.42	5.10

Notes: BN: Batch number; NTP: Number of times processed

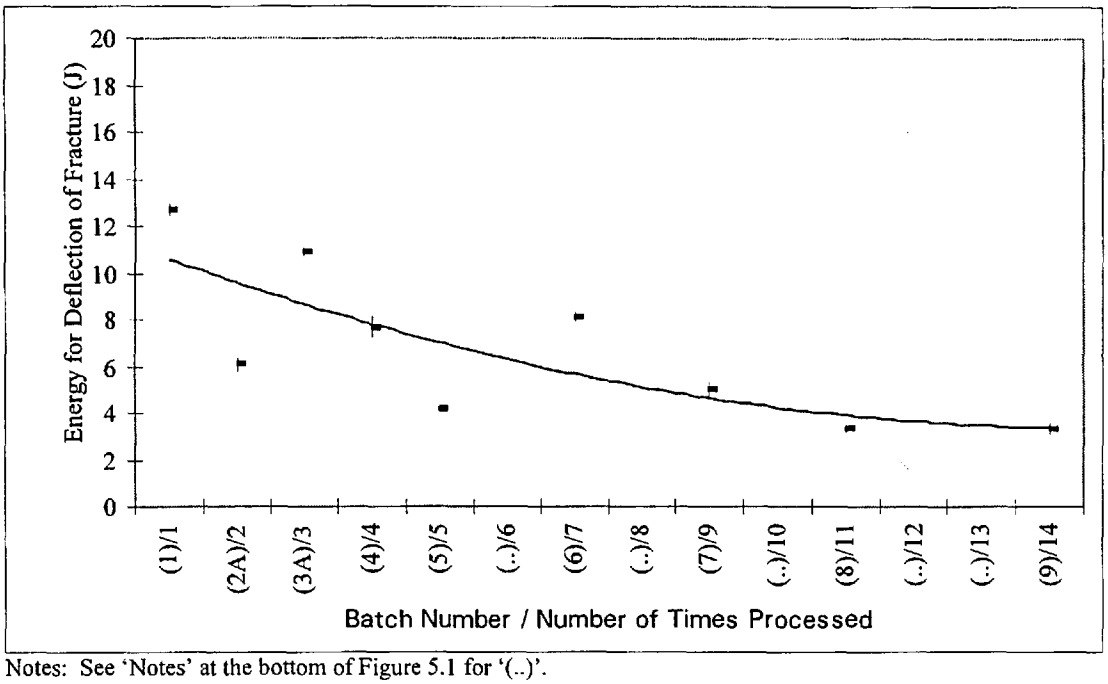
Figure 5.25: **Force** required to **initiate fracture**: Once Processed Virgin Pellets, (1)/1, and General Scraps, (2A)/2 to (9)/14, against their number of processings (±SE).



Notes: See 'Notes' at the bottom of Figure 5.1 for '(..)'.

Accordingly, decreasing trends are found in both the cases of energy required for deflection to fracture and total energy required for fracture and crack propagation as shown in Figures 5.26 and 5.27, respectively. Photograph 5.2 shows the nature and extent of crack on the tested plaque moulds prepared from the HDPE virgin, (1)/1, and general scraps, (2)/2 to (9)/14. In these Figures 5.25, 5.26 and 5.27, mean values with small standard errors suggest that there is an overall distinctive declining pattern for each of the impact parameters studied.

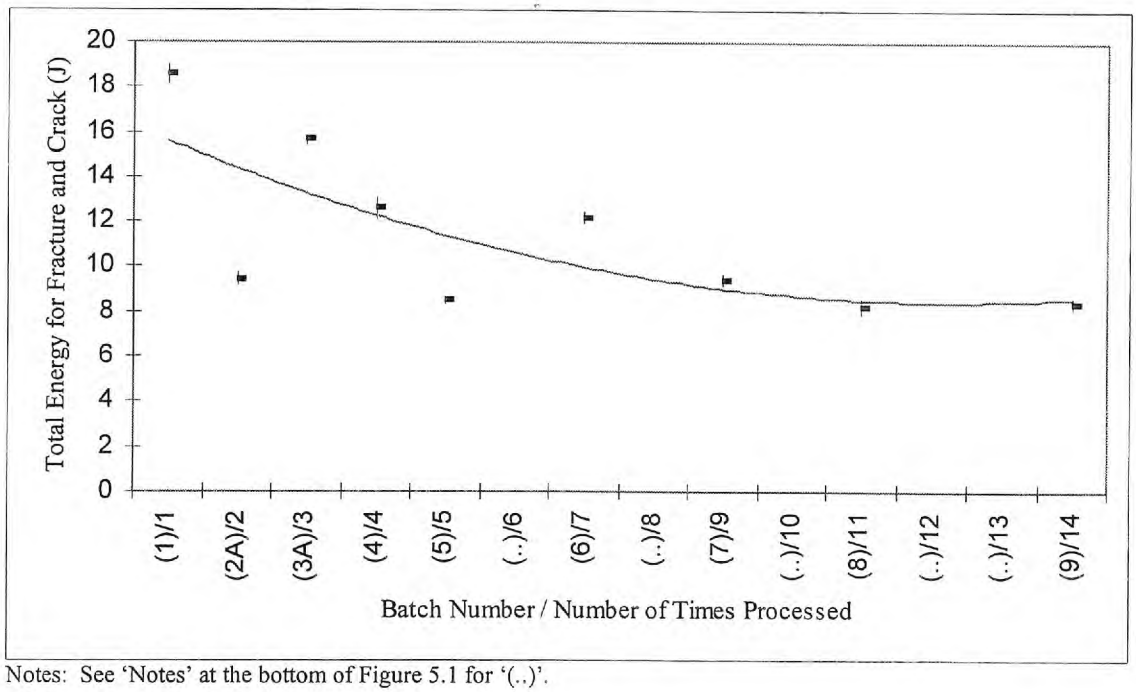
Figure 5.26: **Energy** required for **Deflection of fracture**: Once Processed Virgin Pellets, (1)/1, and General Scraps, (2A)/2 - (9)/14, against their number of processing.



Notes: See 'Notes' at the bottom of Figure 5.1 for '(..)'.

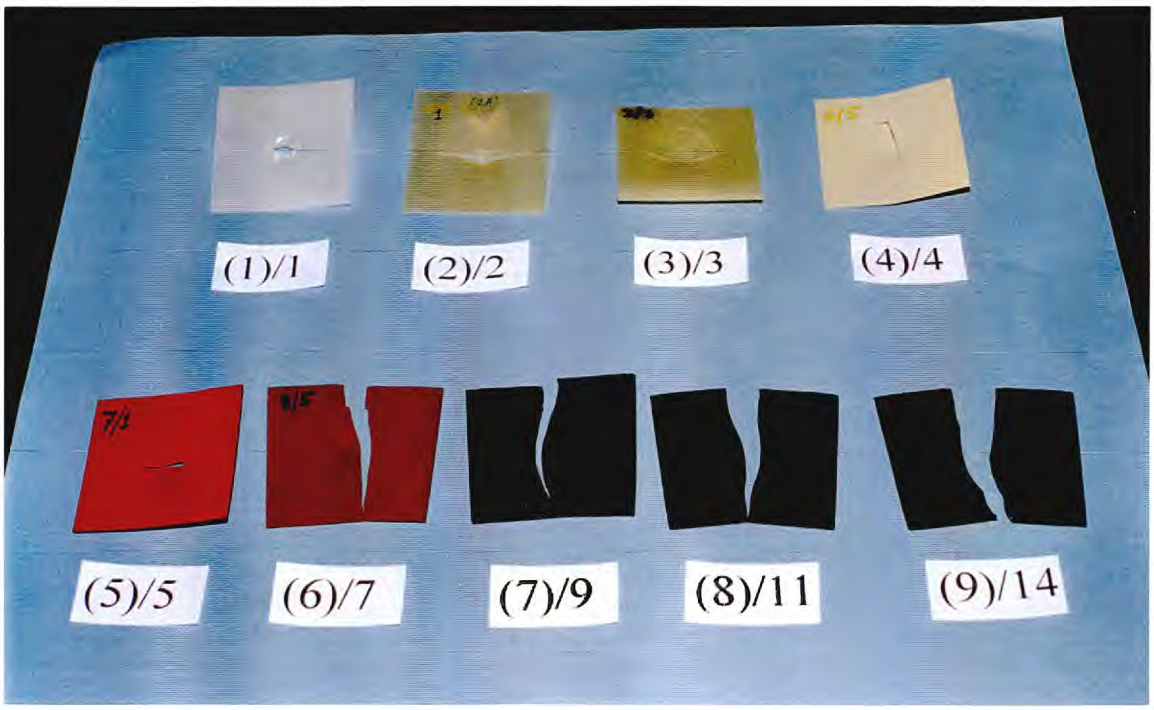
Finally, impact resistance test results suggest that material becomes less resistant to crack initiation in bending as indicated by the reduction in 'force required to initiate fracture (F). This degradation is also evidenced by the fall in 'energy required for deflection to fracture' (E1) from 12.68 J to 3.31 J. Nevertheless, no significant change in 'energy required for crack propagation' (E2-E1) indicates that toughness of the materials remains the same.

Figure 5.27: **Total energy** required to cause **fracture** and **crack propagation** for the Once Processed Virgin Pellets, (1)/1, and General Scraps, (2A)/2 - (9)/14.



Notes: See 'Notes' at the bottom of Figure 5.1 for '(..)'.

Photograph 5.2: Impact strength tested plaque moulds of the HDPE virgin and general scraps processed several times in Bangladesh



5.4.6 Other Factors Affecting Polymer Properties

Polymer properties can be changed not only by shearing or thermal effects of successive processing but also by their intensity of use, nature of use (types of application - indoor or outdoor, contents - corrosive or non-corrosive liquids or solids), length of time in use and/or reuse, level of exposure to ultra-violet radiation, ageing (even in the absence of ultra-violet radiation) and types and proportion of colour pigment contents (Ram and Getz, 1984; Williams and Bevis, 1980a, 1980b, 1981, 1982; Dyson, 1997). As a result, in addition to the deterioration in polymer quality, external appearance and colour of plastic articles also become inferior cumulatively with increasing length of service life and progressive number of recyclings. Considering quality deterioration in the recyclable materials, plastics recyclers in Bangladesh and India commonly add a range of colour pigments with their feedstocks previously recycled several numbers of times in order to make their recycled products attractive and marketable. Nevertheless, depending on types of pigments, some of them accelerate the degradation process and some others prevent the process (Williams and Bevis, 1981). Therefore, here it is important to understand the strength of all these factors including commonly used colour pigments in causing deleterious effects upon the properties of the HDPE studied.

In this investigation, very little attempt was made due to shortage of time and resources to determine and compare some of the properties of four different jerry-cans. These had been in use for different lengths of time in different applications within the tropical climatic conditions of Bangladesh. The first jerry-can was made of a particular grade of virgin HDPE. The other three jerry-cans were produced during the last few years using presumably the same grade of virgin HDPE. Here it is necessary to explain (i) how it was understood that all four sample jerry-cans collected from Dhaka were made of same grade of virgin HDPE, and (ii) what was the basis of identification that a particular jerry-can had been in use for a certain length of time. The best available basis of this understanding /assumptions are as follows:

- All four sample jerry-cans collected and tested were moulded with the same names of their manufacturer-cum-supplier and first commercial user.
- It was understood on the basis of the responses from the manufacturer that, according to product specifications demanded by the commercial user, jerry-cans of the same size, capacity and design as these samples have been produced by

the manufacturer for last 10-13 years using mostly a particular source of HDPE virgin pellets (Mobil HYA 600, product of Saudi Arabia).

- Service life spans of these sample jerry-cans were estimated as best as possible, based on the available information gathered from general observation in every day life, field work and interviewing informally 100 housewives by demonstrating the jerry-cans to them. In most cases a longer life span was given to the sample jerry-can with the worst condition as a result of normal use for a longer period, intensive use for a shorter period or unusual application for a shorter period.

In Figure 5.28, significantly higher MFR values are obtained for the jerry-cans which had been in use for a longer period. Accordingly, without any statistical significance, a slightly decreasing trend in stress at break property with the increase in life span is shown in Figure 5.29. In the case of stress at yield and strain at break properties, their mean values are randomly distributed with no definite trend of change due to the effect of length of use (Figure 5.30 and 5.31). One of the possible explanations of their similar tensile strengths is that all four sample jerry-cans were moulded from unpigmented translucent virgin pellets by one processing step.

Figure 5.28: **Melt flow rate** vs. **service life span** of once processed HDPE jerry-cans.

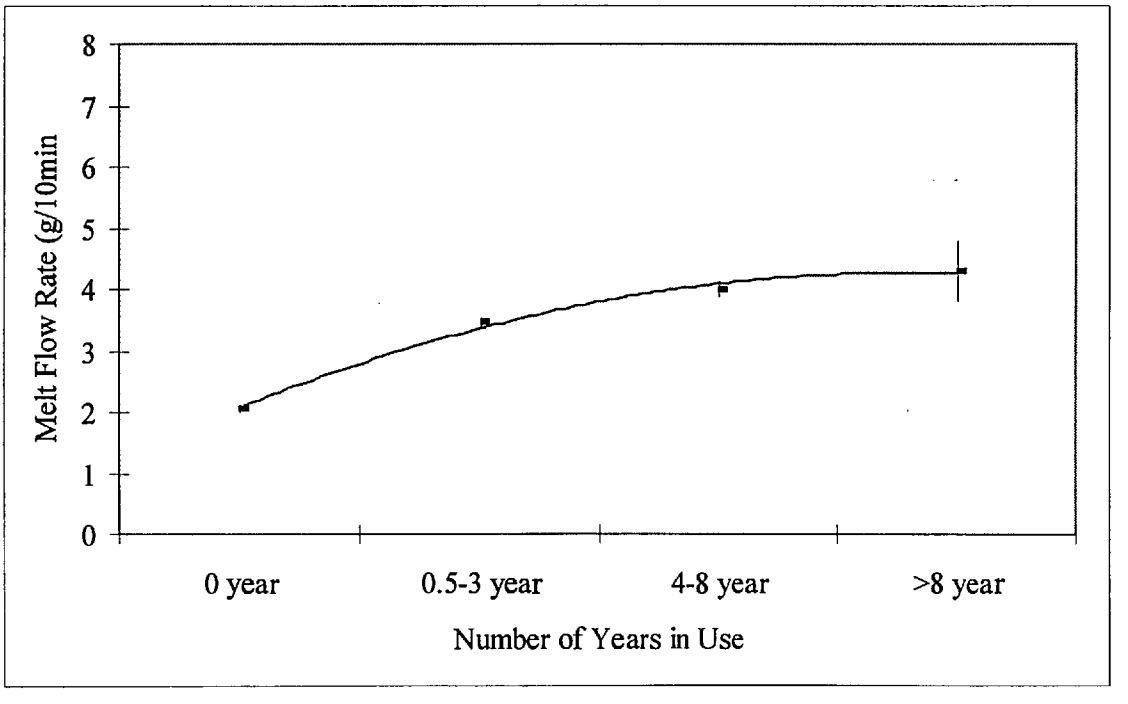


Figure 5.29: **Stress at break** vs. **service life span** of once processed HDPE jerry-cans.

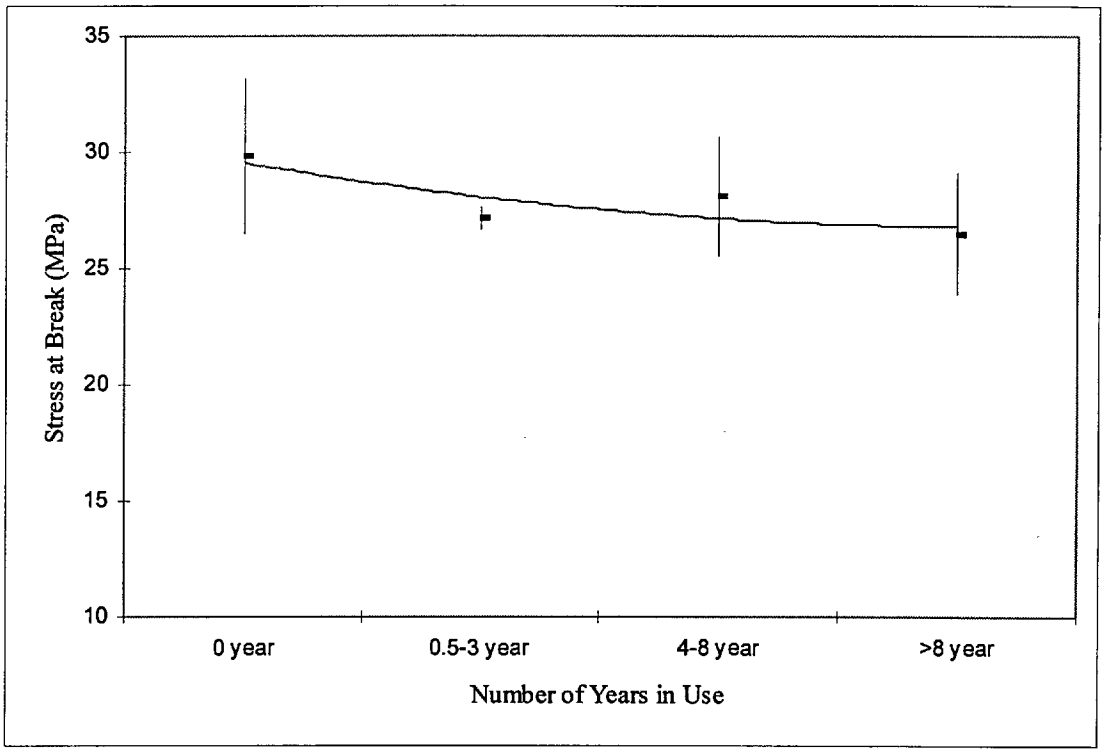


Figure 5.30: **Stress at yield** vs. **service life span** of once processed HDPE jerry-cans.

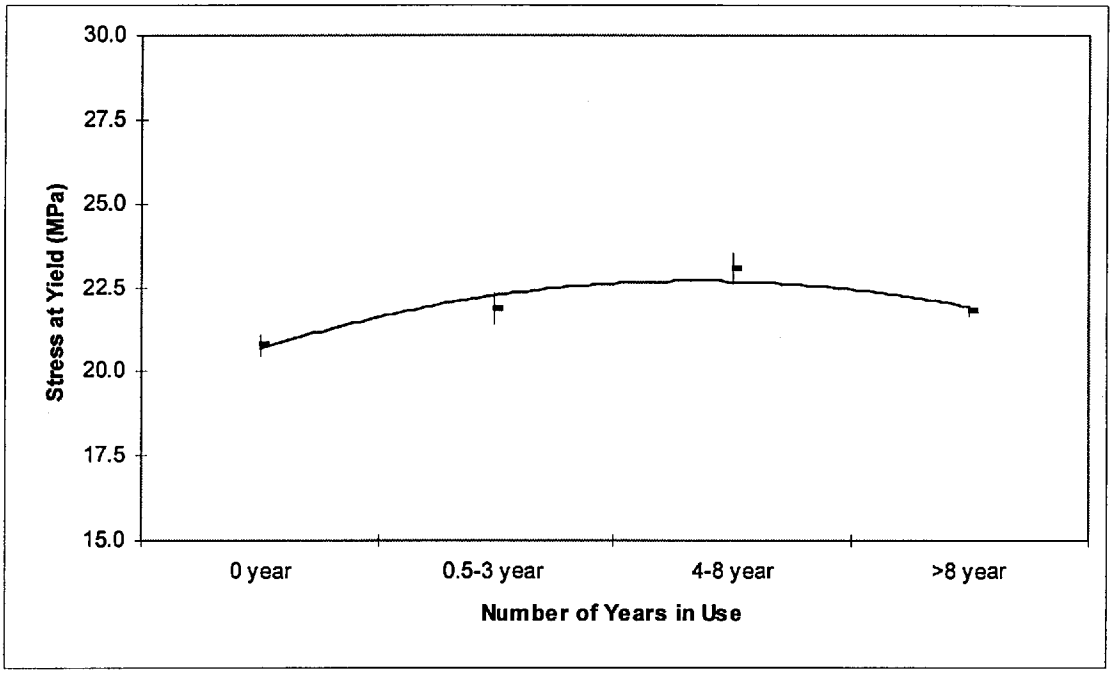
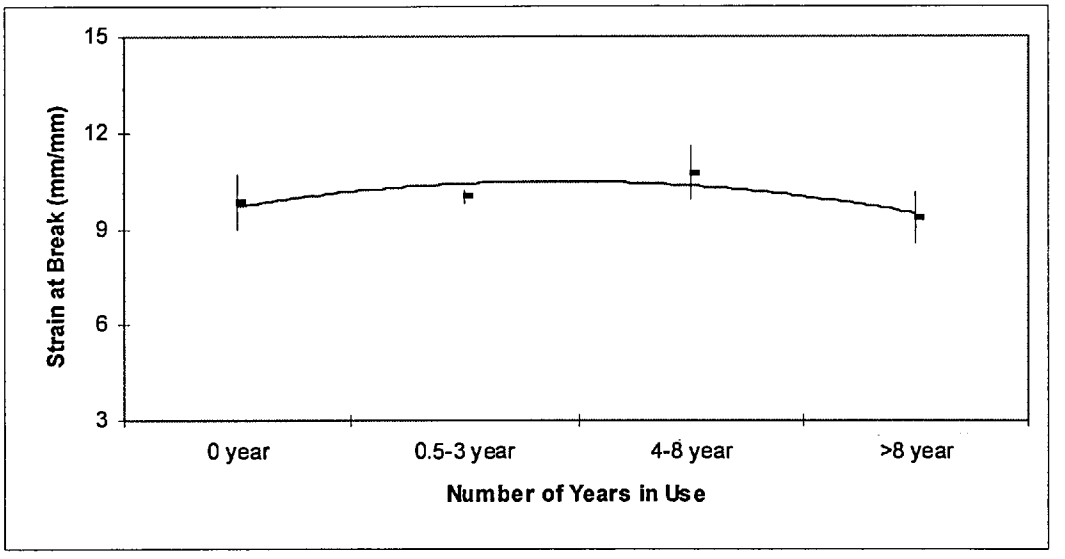


Figure 5.31: **Strain at break** vs. **service life span** of once processed HDPE jerry-cans.



5.5 Discussion and Conclusions

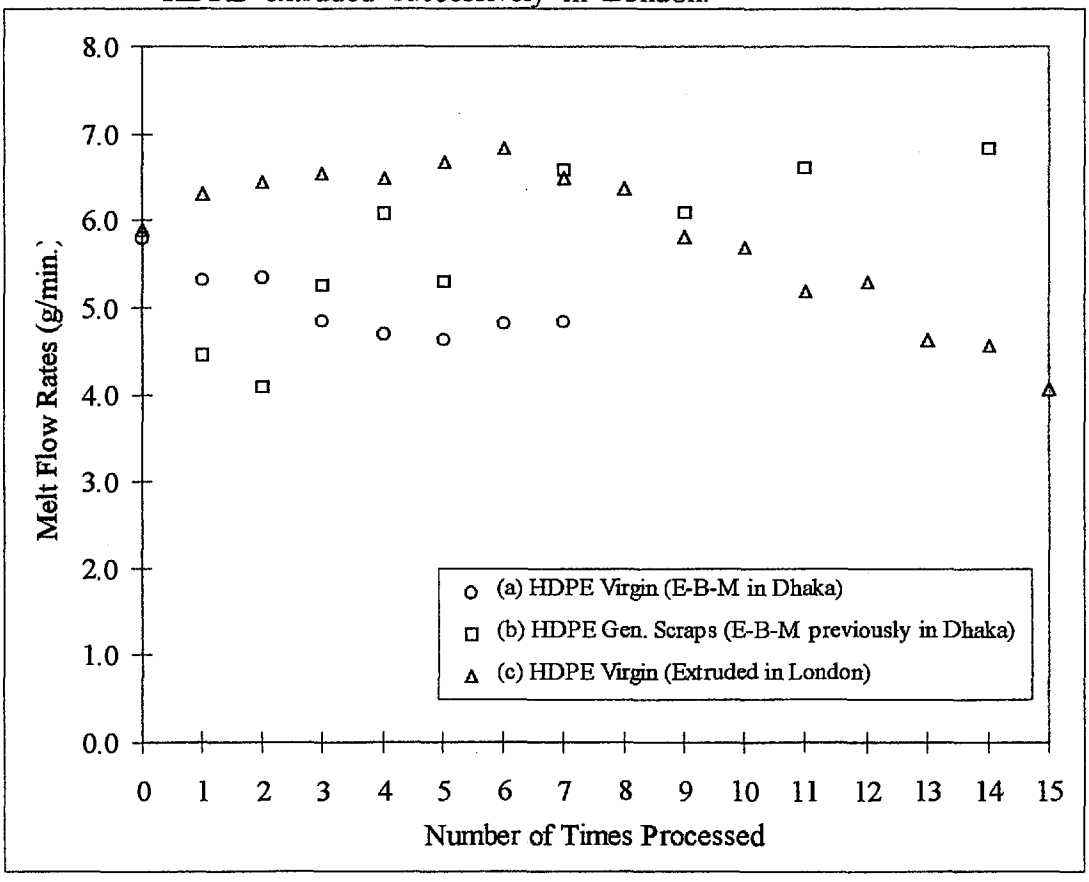
It has been shown that marked and systematic changes in mechanical and rheological properties of HDPE virgin and general scraps from Bangladesh and India do occur with increasing number of successive processings. A comparison between the MFR test results of the materials successively 'extruded' from the virgin HDPE in London (Chapter 4) and those successively 'extrusion-blow-moulded' from the same batch of virgin material in Dhaka, shows a substantial difference in their melt flow rate (Figure 5.32). There are four main impetuses for the reported differences as in the following:

Firstly, the virgin HDPE materials were successively processed using two different machines under different processing conditions. A manually operated single screw extrusion-blow-moulding machine (operated at an average barrel temperature of 177 ^{0}C, Chapter 3) was used at Dhaka whereas an automatic twin screw extruder set with a temperature of 200 ^{0}C was used at London. As a result there is an absolute difference in experiencing thermal effects by the materials due to the difference in processing conditions involved. Higher MFR values for the case of London suggest that the virgin material may be affected by higher thermal degradation as they were reprocessed at relatively higher processing temperature.

Secondly, different forms of sample specimens were used in MFR determinations. In the case of Dhaka, irregular shaped flakes cut-off from the moulded jerry-cans were tested and on the other hand, in the case of London, regular shaped rod pellets were tested. For instance, irregular shaped flakes may have not been melted properly during MFR tests, and thus, created obstructions to their steady flow through a die of diameter 2.09 mm. This could account for a significant difference in the measured values of MFR, but the exact cause of this effect remains unknown.

Thirdly, sample specimens collected from Dhaka and those prepared from successive extrusions in London were tested after 5 months and one week, respectively, which may cause some secondary effects due to their ageing. A marked deterioration in the impact strength performance was observed by Williams and Bevis (1982) when natural co-polymer's plaques (having no ultra-violet stabiliser) were tested after 6 month ageing the absence of ultra-violet radiation.

Figure 5.32: A **comparison** between **MFR** values measured for three different sets of the specimens prepared from: (a) virgin HDPE extrusion-blow-moulded (E-B-M) successively in Dhaka; (b) general scraps previously processed (E-B-M) several times in Bangladesh; and (c) the same virgin HDPE extruded successively in London.

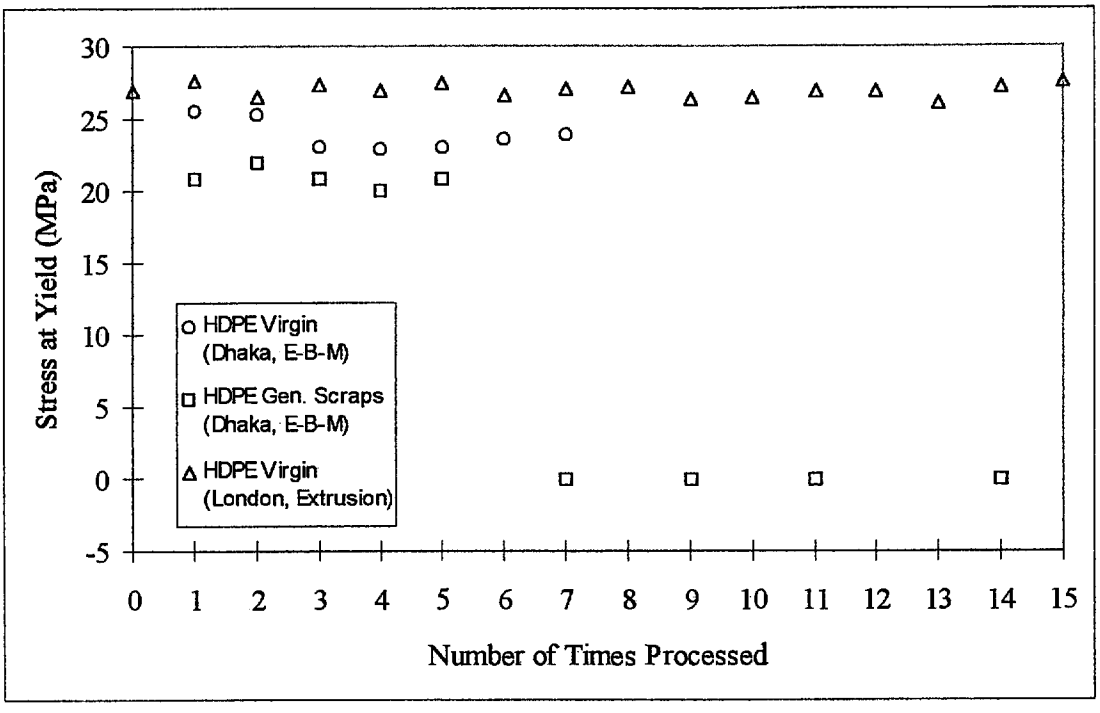


Fourthly, this obvious difference also could result from the unavoidable impurity contents in the flakes specimens from Dhaka which may have also obstructed the flow of extrudates. Extraneous particles are inevitably added into the feedstocks with the increasing number of successive processings. This generally occurs in the case of plastics recycling in Bangladesh and India because the mouldings, sprues and runners are collected and piled up on floor and then shredded into flakes but again these are collected on the floor due to the design of machines involved. The proportion of these extraneous particles was low in the case of the materials reprocessed in London as the extrudates were pelletised and collected in a clean container.

General scrap plastics already get cross-contaminated with other wastes and some proportion of these contaminants remain with the recovered materials even after the cleaning and washing stages. Besides these contaminants, extraneous particles are also added inevitably with general scrap feedstocks during processing stages (shredding, pelletising and moulding) in Dhaka as in the case of in-house processings. Therefore, it is reasonable to expect that further lower values of MFR could have been occurred for the general scraps due to their relatively higher content of extraneous substances. Nevertheless, a ***contradiction*** arises here in explaining the effect of extraneous substances upon MFR values, as higher MFR values were determined for the general scraps previously processed more than 7 times in Bangladesh (Figure 5.32). Therefore, all these factors probably have a secondary effects on the properties of the general scraps but the primary effect is thermal degradation during the past recycling cycles. Furthermore, increase in MFR may also be attributed to the effects resulting from the nature and length of use of plastic products.

The stress at yield values for the virgin HDPE processed both in Dhaka and London do not suffer from a significant change with increasing number of processings, but the values for general scraps experience a drastic fall indicating brittleness after around five or six times processings (Figure 5.33). This fall will be affected by all the different factors discussed above causing deleterious effects cumulatively, following the existing waste disposal and recycling system in Dhaka.

Figure 5.33: A **comparison** between three different sets of **stress at yield** values measured for the dumb-bell specimens prepared from: (a) virgin HDPE extrusion-blow-moulded (E-B-M) successively in Dhaka; (b) general scraps previously processed (E-B-M) several times in Bangladesh; and (c) the same virgin HDPE extruded successively in London



In the case of all three sets of stress at break results as shown in the Figure 5.34, reduction in the break values occur with the increase in the number of processings. Irrespective of the advantages of reprocessing under known processing conditions using an automatic twin screw extruder in London, the stress at break values obtained for the virgin HDPE are lower than the values determined for the general scraps and the same Virgin material reprocessed in Dhaka. Here it is interesting to note that the successively reprocessed virgin materials in the case of London are weaker than both the virgin and general scrap materials from Dhaka, but answer to the causes of these types of results remain unknown and indicates need for further research.

In Figure 5.35, three different sets of strain at break values are in accordance with the reasons of variations normally expected, i.e. the lower the mechanico-thermal degradation and also the lesser the content of extraneous particles, the higher the strain at break values.

Figure 5.34: A **comparison** between three different sets of **stress at break** values measured for the specimens prepared from the HDPE virgin and general scraps collected from Dhaka.

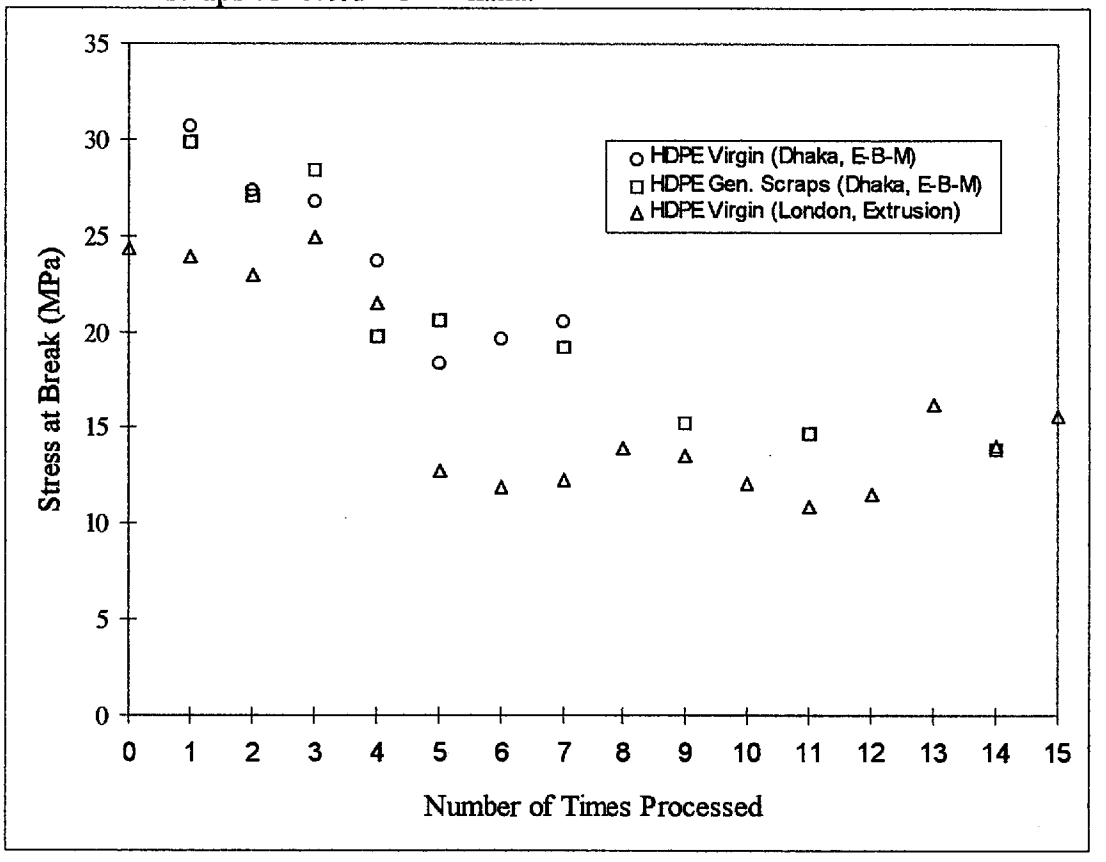
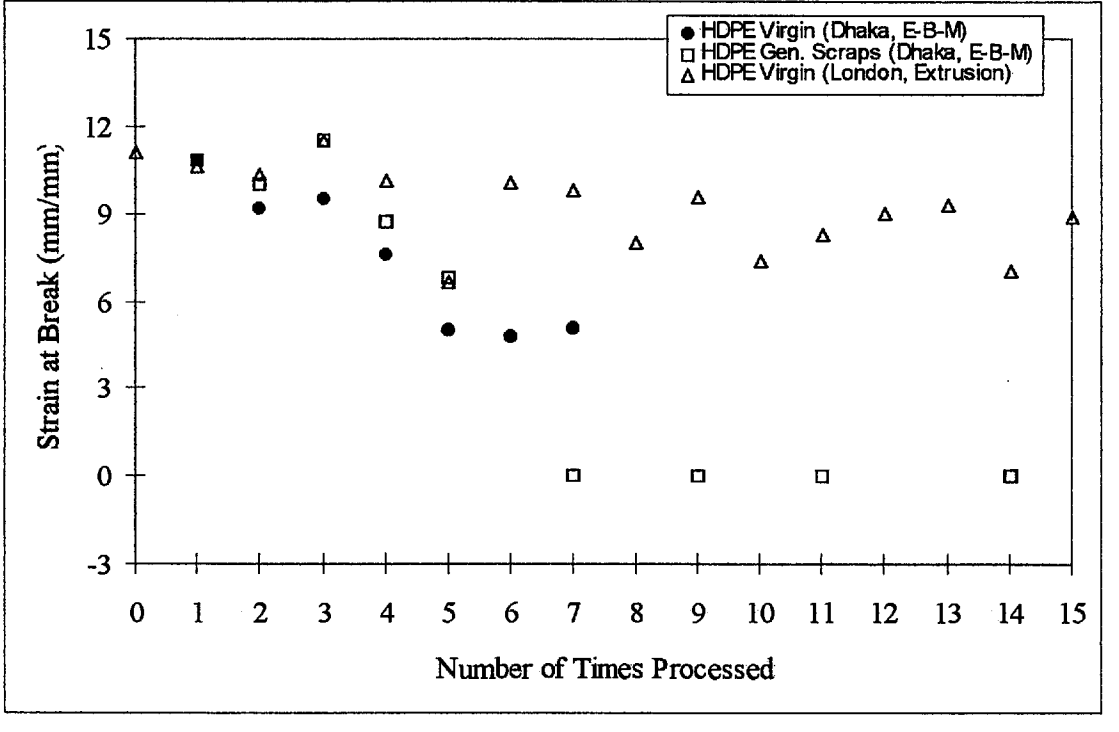


Figure 5.35: A **comparison** between three different sets of **strain at break** values measured for the specimens prepared from the HDPE virgin and general scraps collected from Dhaka.



A slightly decreasing trend is shown by the results obtained for strain at break values of the virgin material in both the cases of Dhaka and London specimens, but the values for the latter specimens remain higher at all processing numbers compared to other two sets of results (Figure 5.35). These higher strain at break values of the London specimens reflect the lower mechanical degradation when using the automatic twin screw extruder. Accordingly, lower strain at break values of the Dhaka specimens, even a drastic fall for the general scraps, show the deleterious effects resulting from higher mechanico-thermal degradation of reprocessing under unknown processing conditions using single screw pelletising and moulding machines (Figure 5.35). Presence of extraneous substances in the general scraps may well be an important reason for the fall in their strain at break values.

Moreover, general scraps could have suffered from the effects resulting from the effects of length and nature of use determining their level of exposure to ultra-violet light. Since the scraps were usually reprocessed without proper care and maintenance of consistency of processing conditions, they might have lost molecular weight and additives, caused active chain ends, and become more susceptible to the effects of ultra-violet light (Williams and Bevis, 1981, 1982). Their higher level of exposure to ultra-violet light under the tropical climatic conditions for a prolonged period over the course of closed-loop recycling cycles in Bangladesh and India could be another good reason for their property deterioration.

Bearing in mind all these above deleterious effects, test results for the specimens made of the general scraps collected from Dhaka, Calcutta and Delhi cities also show a steady increase in MFR and decrease in tensile strengths measured against their number of processings within the existing recycling systems. These values for the Calcutta and Delhi materials are very close to the values of their corresponding general scraps from the Dhaka waste stream. This is probably due to the similarity in the method of plastics waste disposal, recovery and processing systems and equipment employed in these cities. Moreover, this closeness in the results may also be due to an accurate judgement which was made in identifying the 'number of times processed previously' for the general scraps collected.

Nevertheless, irrespective of the conditions of feedstock and quality of recycled products, plastics recyclers in Bangladesh and India keep using all variety of scrap plastics for a range of applications following a preferential basis. For instance, 11 times processed dull black HDPE granules are generally used for producing jerry-cans by extrusion-blow-moulding and give jerry-cans processed 12 times. If jerry-cans fail to hold air blown at the moulding stage, then more material is allowed to extrude so that puncture will not occur because of thicker walls. These jerry-cans with thicker walls still possess some value not entirely due to their polymeric performance but to their relatively strong structural capacity to act as containers. If the moulds are unable to hold air blown even after extruding enough material, then this lot of material will be removed and transported to other recycling units to produce lower grade products by injection moulding where air blow holding capability is not required for the feedstocks. In the next cycle of recycling, this lot of 12 times processed jerry-cans or other form of injection moulded products may be or may not be recycled any more times, depending on their overall physical condition.

As this is the case for recycled plastics in Bangladesh and India, an important question needs to be asked as to what would be the ultimate destination for the recycled plastics whose properties are degraded to such a level that the material become unsuitable for any more recycling. In order to elucidate this little studied problem in plastics recycling, mathematical models have been developed and illustrated in the next Chapter 6 to determine future scenarios of plastics recycling and landfilling in these countries.

CHAPTER 6:

Mathematical Modelling of Plastics Recycling in a Developing Economy

6.1 Introduction

Future policy formulation for regulating plastics recycling and introducing legislative measures for landfilling non-recyclable plastics should be based on some scientific and practical grounds derived from a real data base. These attempts are required to support quality control of the recycled products and also to maintain a better environment in any country of the developing or developed parts of the world. In this regard the data base should comprise a range of information on all different types of plastics in terms of their (a) annual production, imports and exports, (b) amount recovered and recycled, (c) service life span (or time interval between two successive processings for recycling), (d) year of imports, production, recovery, reprocessing, and exports, (e) number of times processed using traditional or modern machines, (f) amount of different plastics categorised by their types, number, and year of processing, (g) quality of these plastics categorised by number of processings, impurity contents, and type and proportion of additives, (h) total amount of landfilling in a year, and (i) quality of plastics landfilled.

In the case of a country suffering from an insufficient data base of this kind, for instance, Bangladesh or India, computer simulation based on the existing available information could be used as a tool to predict: (i) the future amounts of recovery, (ii) the composition and quality (against number of times processed) of different types of recycled plastics, and (iii) amounts of plastics landfilled per year in the next decade. This tool could also be used in the future decision making within the plastics recycling arena of the country concerned.

In accordance with the ultimate goal of this study i.e. to develop some future scenario models for plastics recycling and landfill, all available information on plastic imports and recycling in Bangladesh and India has already been gathered during the fieldwork, and described in Chapter 3. In addition to this information, a number of mechanical and rheological properties of different batches of HDPE collected from these countries were determined against their successive number of processings, following the standard laboratory procedures. These experimental results were analysed and discussed critically and were presented in Chapters 4 and 5. Besides this available information and experimental results, there is still a need to develop a number of mathematical models in order to determine the future scenarios of plastics recycling and landfilling in

Bangladesh and India. Mathematical modelling permits consideration of a very large number of variables and factors, in order to achieve more accurate results. It also provides the opportunity to perform many simulations over a range of future scenarios in a relatively short computation time. However, modelling of these scenarios requires extensive calculations to be considered quantitatively.

Accordingly, in this chapter, attempts have been made at mathematical modelling with the aid of digital computers to address this issue and deal efficiently with the plastics recycling system in Bangladesh only. In this study, however, the reasons for such attempts at developing a number of mathematical models for plastics recycling in Bangladesh are that (a) imported virgin pellets is the single primary source of plastics of the country, (b) the markets for both new and recycled plastic products are almost entirely confined within the country, and (c) thus a low number of modelling parameters were required for consideration in developing the models and to complete this modelling exercise within the limited scope of time and resources given. On the other hand, in the case of the other two case study countries of the current study - India and United Kingdom, a wider market and a network of international linkages are in operation for both importing and exporting their plastic raw materials and products. Moreover, the socio-economic aspects and underlying impetus which provide support for achieving a higher rate of plastics recycling in Bangladesh are more or less the same as those involved in the case of India (Chapter 3), but these are in direct contradiction to the case of the UK according to the findings from literature research (Chapter 2). Therefore, these types of mathematical models could also be developed for predicting and planning waste management problems of these countries, but the models for any of them should be developed on the basis of their own sets of modelling parameters specific to the problems under investigation.

6.2 Objective of Modelling

The objective of modelling is to determine the future scenarios of Polyethylene (PE) recycling and landfilling in Bangladesh and evaluate them quantitatively by developing some mathematical models, considering the trend of virgin PE imports, its recovery/recycling and landfilling rates, quality of recycled PE against their number of

successive processings, and measures (if any) for better control and management of PE waste.

6.3 Approaches to Modelling

The mathematical modelling task started with identifying and defining the *existing processes* of plastics recycling and landfill in Bangladesh as a part of a 'wider system' of international trading of plastics and its products. An attempt was made to distinguish the 'subsystems' that make up the closed-loop recycling system in Bangladesh, leading to decisions on which aspects/processes of this plastics recycling should be modelled. The reason behind this attempt is that the success of the application of such models for improved waste management in this country depends on how effectively this study is able to anticipate the questions (presented in section 6.4 of this chapter) that will be asked, and then assess these to decide whether they justify building some forms of model. The information gathered from the fieldwork and laboratory experiments (Chapters 4 and 5) was used for explaining some of the subsystems, in order to support the decisions required to be made. A decision was made during the establishment of the *objectives* of this modelling study *to determine the future scenarios of PE recycling and landfilling in the country*, through investigations of the answers to a number of questions about the existing processes which arose before starting the modelling task.

At this step, other fundamentals of modelling i.e. *parameters* and *assumptions* were resolved. Determination of the modelling parameters was followed by setting a number of assumptions needed in building the models. Some efforts were made to establish the basis of the assumptions made in the modelling.

The next step was to conceptualise alternative scenarios for both recovery and landfilling of PE on the basis of these parameters and assumptions. Since the future always involves some degree of uncertainty, allowances have been made to consider the minimum and maximum ranges of the uncertainty in the amount of recovery and landfilling PE wastes. These were done by repeating the analysis with the optimistic and pessimistic values for the parameters subject to uncertainty, and so two alternative scenarios - ***faster scenarios*** and ***slower scenarios*** - were derived for each of the recovery and landfilling activities.

Before developing the future scenario models, some important concepts used in modelling need to be explained.

All alternative scenarios were then brought into models and presented in the form of diagrams. In order to assess these scenario models quantitatively, all necessary mathematical equations were developed, preceded by a phase of creating a data storing procedure which is common for all the different scenarios modelled. Eventually, two separate computer programmes were written using FORTRAN 77 programming language (Monro, 1989) for quantitative evaluation of the scenarios. Using these results of mathematical modelling, attempts have also been made to illustrate graphically the future scenarios for the amount of PE to be imported, recovered and landfilled in Bangladesh during the next decades.

Finally, all other possible scenarios have been discussed and evaluated, considering some necessary hypothetical situations and legislative measures which may appear in the future for managing the plastic waste in Bangladesh.

6.4 The Stages of the Mathematical Modelling

6.4.1 Defining the Fundamentals of Modelling

The following fundamental aspects are inherent in modelling:

a) ***Processes*** which give basic structure of the model. These processes are inter-linked with each other. In this study, the term "processes" is used to refer the dynamics of each sequence in a closed-loop system of plastics 'production/import-consumption-discarding-and-recycling' through treating the waste materials by changing their state, and then, moulding them into finished products.

b) ***Parameters*** defining the rates or characteristics of these processes.

c) ***Assumptions*** which are needed in defining both the processes included in the model and the parameters used to define them.

a) Processes defining the basic structure of the model

- What is the primary source of PE for Bangladesh? Is it being produced within the country or imported from abroad? No PE is produced in the country. Importation is the only primary source of virgin plastics in the country. Virgin PE pellets are imported mainly from Singapore, Korea, Hong Kong (China), Japan, Thailand, Germany and Saudi Arabia. Every year these pellets are coming into the system, new products are manufactured out of them and marketed for use in the country. During the past few years, a very small portion of plastics products has been exported.

- Since when has this plastic been introduced and subsequently recycled in Bangladesh? According to the responses of the appropriate persons interviewed informally during field work in Dhaka, Bangladesh has been importing virgin HDPE since the mid 1960s and also recycling discarded plastics over the same period.

- What are the statistics for virgin plastics importation? Are the imports' figures invariably increasing or decreasing over the years? Is there any linear or non-linear temporal pattern in importation which can be established? Because of a lack of available information on the imports statistics since mid 1960s, Figure 6.1 shows annual imports of virgin Polyethylene (HDPE and LDPE) into the country only for the years of 1990-91 to 1994-95 (Table 3.4 in Chapter 3). No separate data were available separately for the HDPE imports in the country. Figure 6.1 reveals that importation of the material is increasing linearly over the years following the equation below:

$$y = 2.08\chi + 6.23 \qquad \text{(Eqn. 6.1).}$$

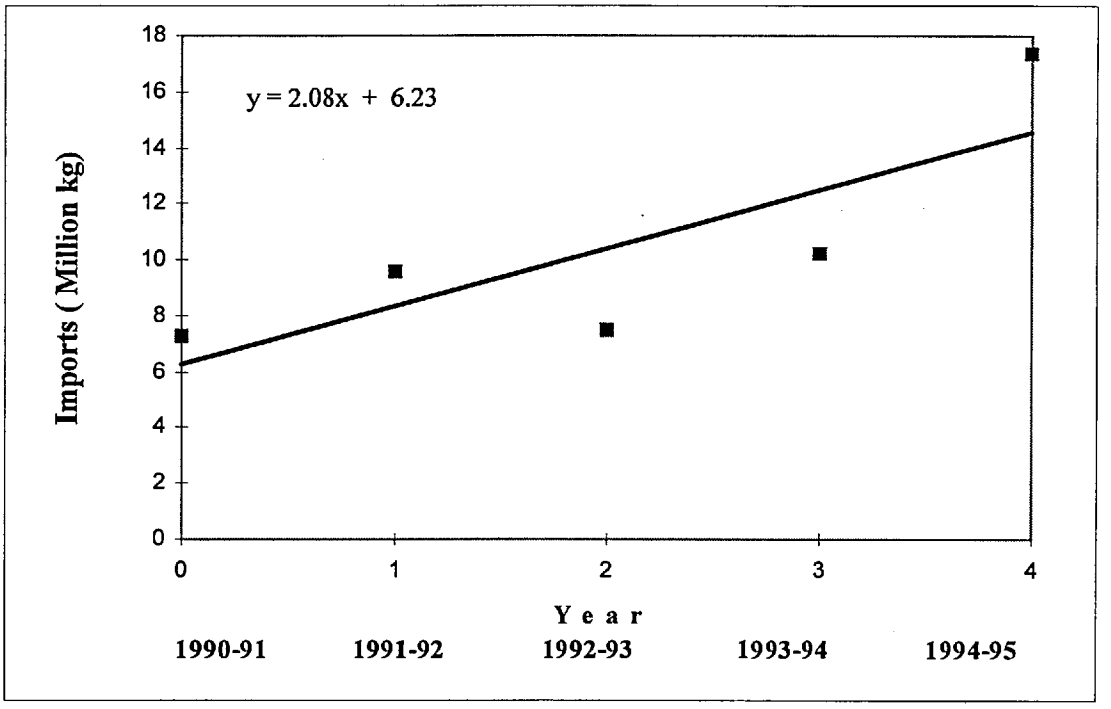
where, χ = Number of years passed from the base year

y = Imports on the corresponding year, χ.

Note that imports values increased by 2.4 times over only a five years period, although the import data points in 1992-93 and 1993-94 are below the linear line. This is probably due to the fall in overall importation as a consequence of the political instability and thus economic depreciation in these years resulting from the fall of the 1990s' government, presence of the temporary caretaker government and

formation of the new government during 1990-92. Therefore, the linear line plotted in the Figure 6.1 is the best possible line based on the available data.

Figure 6.1: Annual imports of virgin Polyethylene (HDPE & LDPE) into Bangladesh and their linear curve fitting, 1990-95.



Data Source: BB, 1996.

- What are the rates of recovery and landfilling of these waste materials in the context of Bangladesh? In this country, currently a very intensive closed-loop recycling system is in operation so that almost all parts of the plastics discarded after use are recovered for recycling, with the remainder going to landfill. The first and foremost impelling force behind this success in plastics recycling is the country's present socio-economic situation, resulting in a high national demand for low cost recycled plastic products. Based on the general experience and information gathered during fieldwork, it is reasonable to agree that, out of the plastic products marketed in any year, about 95% is recovered and recycled within periods ranging from 2-6 years, depending on their service life span. The remaining 5% as the maximum of non-recyclable plastics is normally landfilled within the same length of time.

- Once the plastic products have been manufactured (or recycled) and marketed, how long does it take for those products to be discarded and recovered for recycling? Is

there any relevant information available either from survey results or secondary sources? It was found from the questionnaire survey that the service life of a range of HDPE articles varied from a minimum of 1 hour (for carrier bags) to a maximum of 8 years (for rigid containers), and their overall average service life was 2.9 years within the developing economic context of Bangladesh (Table 3.2 in Chapter 3).

- Does the length of service life of PE products vary only for the difference in their grades and kind of product even when made from same grade of materials? Does this life span of a product depend also on its nature of use, frequency/intensity of use, indoor or outdoor use which cause differences in quality deterioration due to their exposure to ultra-violet radiation? Generally, the answer is that products' life span differs according to the deleterious effects of each of these factors.

- How many varieties of recovered plastics previously processed a different number of times are getting into the closed-loop recycling system of the country in different years? How many times do specific types of waste plastic get recycled within a particular period of time? According to the results of the fieldwork, a higher level of knowledge and skills are required to identify all different varieties of HDPE present in the system according to their number of times processed (see subsection 3.4.1 in Chapter 3 and 2nd paragraph of subsection 5.4.1. in Chapter 5). A large variety of HDPE general scraps are present in the system with different processing numbers ranging from never processed virgin pellets (round shape; Pro-0) to 13/14 times processed very dull-black materials (in scraps or granules form; Pro-13/14). It has already been discussed that over the course of 5 to 6 closed-loop recycling cycles operating in Bangladesh, HDPE scraps are generally passed through 13 or 14 melting stages (for processing: pelletising, agglomerating-granulating or moulding). Depending on the average service life span of HDPE articles, or in other words, length of 'recovery time step' (which is explained in the next section of this chapter), discarded HDPE material needs a total of around 15/18 years to become 5/6 times recycled (or 13/14 times processed) material (Figure 3.4 in Chapter 3).

- What are the land and water pollution risks associated with the quality deterioration of recycled plastics and landfilling non-recyclable plastics? In the course of increasing environmental awareness and development in the country, there may be a good chance to introduce new legislative measures that permit 'no more recycling after a batch of waste plastics has been processed a particular number of times'. For

instance, after 4-6 number of successive reprocessings, HDPE from Dhaka declines significantly both in its mechanical and rheological properties as has been evidenced by the experimental results described in Chapter 5. Therefore, is there any possibility of such deterioration ultimately resulting in landfilling of a very large amount of useless/non-recyclable plastics which may have great potential to cause serious land and ground water pollution? What would be the increase in landfilling of plastics on top of the current level of landfilling of non-recyclable plastics, if such legislation mentioned above is introduced at some point in the future?

- In view of the experimental results and all these questions discussed above, what are requisites for modelling future scenarios of plastics recycling in this country, and how could the results out of these modelling exercises be useful for the future plastic waste management in developing countries like Bangladesh?

Since these questions could not be answered by simple isolated calculations, but required the evaluation of a considerable proportion of the total system, therefore the use of a mathematical model was advantageous in assessing the scenarios. Moreover, these calculations are not trivial and required to be repeated a number of times, and thus serious consideration was given to the development of mathematical models using FORTRAN 77 language.

b) Parameters making up the models

The following parameters have been used in building up the scenario models:

(i) Trend in PE import,

(ii) Recovery percentages,

(iii) Recovery time steps,

(iv) Landfilling percentages,

(v) Landfilling time steps,

(vi) Year of imports, year of recovery and year of landfilling, and

(vii) Calculation year.

How all these modelling parameters are involved in this mathematical modelling is defined and elaborated with necessary examples in the following subsections related to 'assumptions' and 'concepts' included in the modelling.

c) Assumptions made for building models

A number of assumptions are made to define both the processes and the parameters involved in this modelling study. For this purpose, the following assumptions have been made:

- Due to lack of available data from the first year of plastic importation into the country (which was around mid 1960s), the present model is designed to start from 1990-91, assuming that this is the beginning year of virgin PE imports. It is assumed as the base year for the models and is defined as 'Year 1' (Y_1). It also considered that there were no other forms/types of plastic existing in the market except the virgin PE imported in that year.

- It is assumed that PE imports into Bangladesh are increasing linearly over the years following the equation of '$y = 2.08x + 6.23$' (Equation 6.1 based on Figure 6.1).

- Although it has already been mentioned that plastics recycling in Bangladesh is operating within a closed-loop system, it is assumed further that all plastic materials or products either made of virgin pellets or recyclate are confined within the borders of the country. None of these materials were exported from the country in any form during the period investigated.

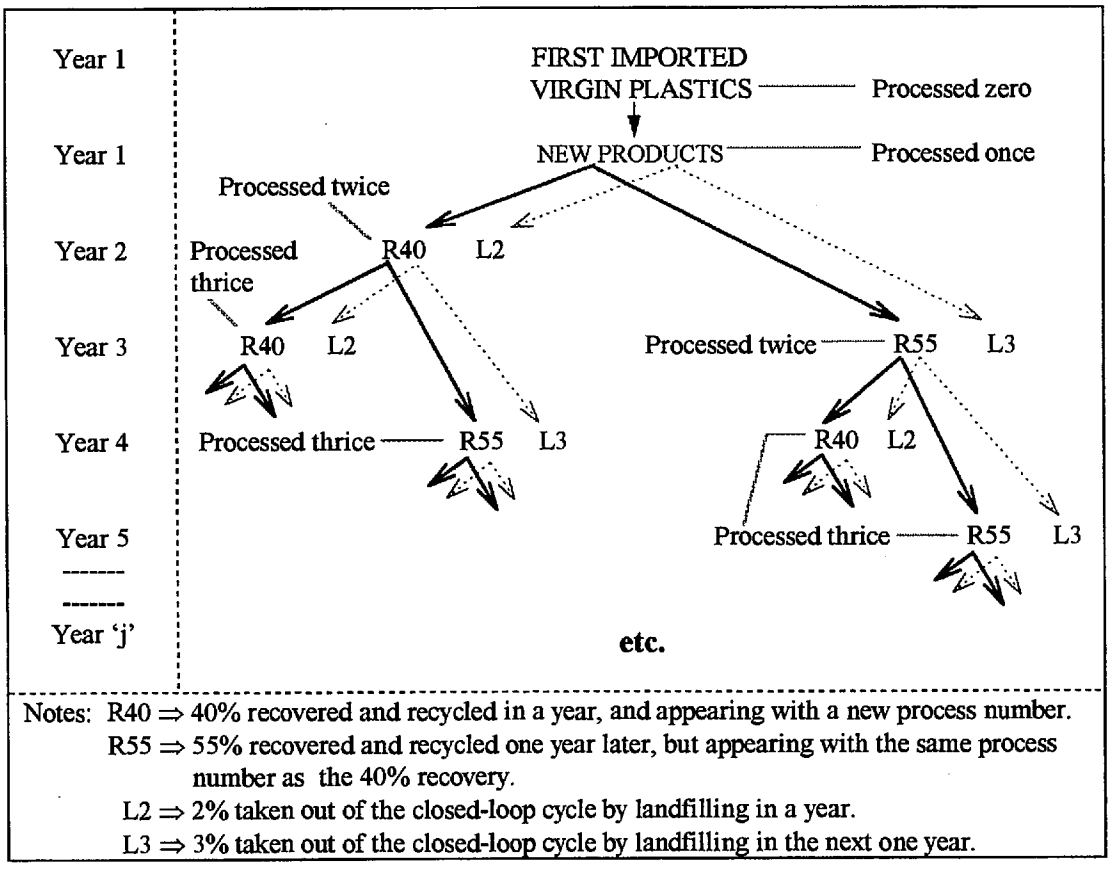
- However, in order to address the two extremes of service life span (1 hour to 8 years) of PE products , the following two separate rates of recovery and landfilling are considered:

    - **Faster recovery scenario (1 year time step)**: Considering the rapid discarding and recovery pattern under this scenario, it is presumed that at any stage of the closed-loop recycling system, 95% recovery for any lot of

products requires a total of 2 years since the lot has been marketed. It is also postulated that a 1 year period is required by the products to be used up and discarded only.

* First 40% of any lot of products is discarded and recovered in the *first 1 year time step* (e.g. R40 in Year 2) since these materials were marketed (e.g. in Year 1) as shown in Figure 6.2;
* Another 55% is discarded and recovered in the *second 1 year time step* (e.g. R55 in Year 3) since the lot of materials were marketed (as shown in Figure 6.2).

Figure 6.2: Faster recovery and landfilling scenarios within the closed-loop recycling system in Bangladesh.



◊ **Faster landfilling scenario (1 year time step)**: Under this faster scenario, the remaining 5% of the same lot discussed above is landfilled within the same 2 years of the 95% recovery.

* First 2% is landfilled in the *first 1 year time step* (e.g. L2 in Year 2) since the materials were marketed (e.g. in Year 1) as shown in Figure 6.2; and
* Another 3% is landfilled in the *second 1 year time step* (e.g. L3 in Year 3) since the lot of materials were marketed (as shown in Figure 6.2).

◊ **Slower recovery scenario (3 years time step)**: According to this slow discarding and recovery pattern as shown in Figure 6.3, it is postulated that completion of the 95% recovery of any lot of products requires a total of 6 years. However, a 3 years time step is considered for this scenario.

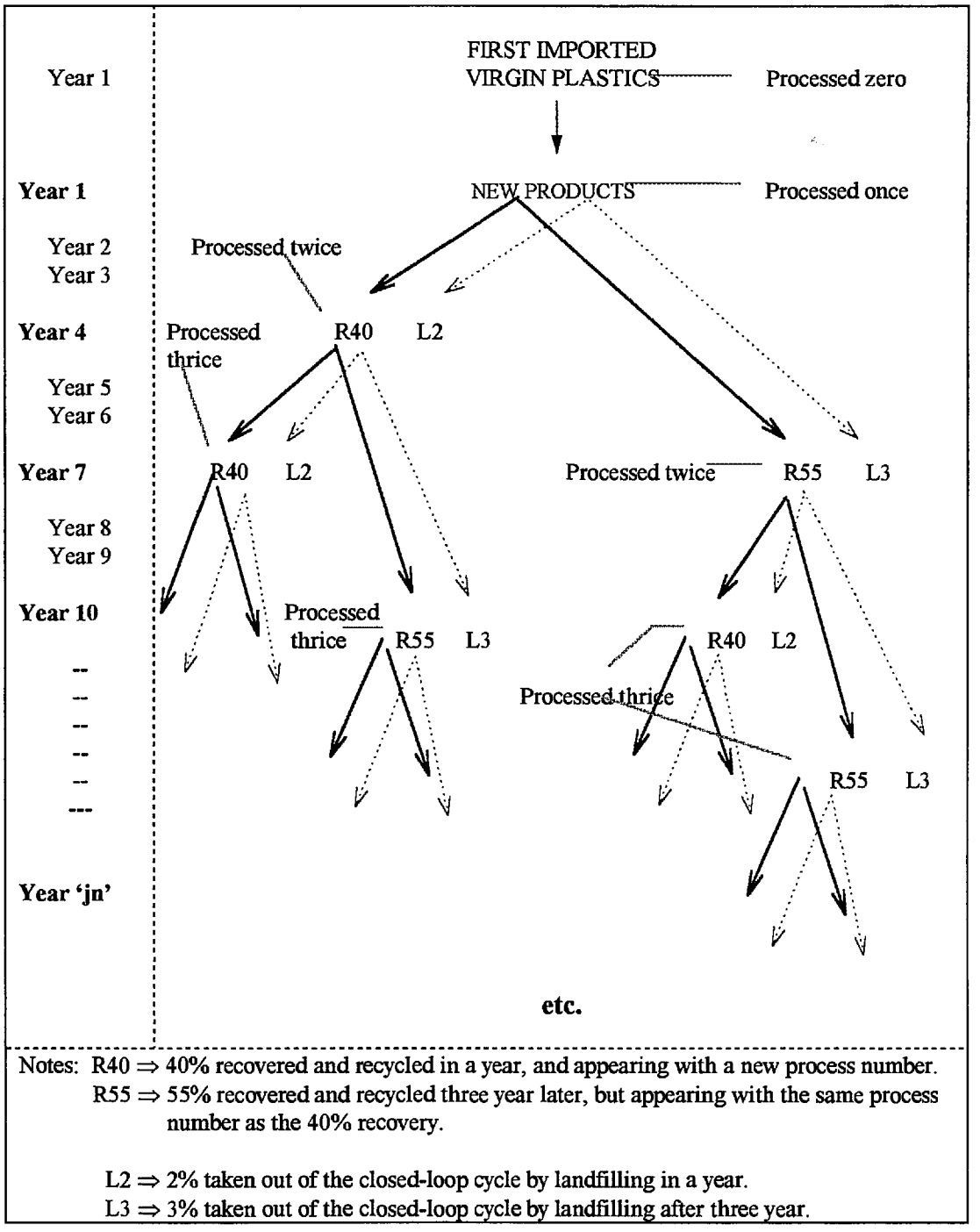
* First 40% of any lot of products is discarded and recovered in the *first 3 year time step* (e.g. R40 in Year 4) since these materials were marketed (e.g. in Year 1) (Figure 6.3);
* Another 55% is discarded and recovered in the *second 3 year time step* (e.g. R55 in Year 7) since the materials were marketed (Figure 6.3).

◊ **Slower landfilling scenario (3 years time step)**: Here it is assumed that, along with the 95% recovery, the remaining 5% of the same lot is landfilled within a total of 6 years, following a 3 years time step of landfilling:

* First 2% is landfilled in the *first 3 year time step* (e.g. L2 in Year 4) since these materials were marketed (e.g. in Year 1) (Figure 6.3);
* Another 55% is landfilled in *second 3 year time step* (e.g. L3 in Year 7) since the materials were marketed (Figure 6.3).

♦ No time gap is considered between the period of importation, manufacturing and marketing. Similarly, no time gap is also considered between the recycling stages of recovery, processing and marketing. In other words, as soon as a lot of the materials is imported or recovered, the materials are immediately processed into products and marketed.

Figure 6.3: Slower recovery and landfilling scenarios within the closed-loop recycling system in Bangladesh.



- It is also assumed that the processes of recovery and landfilling are carried out successively, and the percentages of recovery and landfilling in each time step are fixed in time.

6.4.2 Developing Mathematical Models and Their Computer Programming

6.4.2.1 Mathematical Models

Based on the understanding of the fundamentals of the faster and slower recovery and landfilling scenarios as explained and illustrated in the earlier sections, the following mathematical models were developed by analysing and synthesising the functional aspects of the plastics recycling and landfilling systems currently operating in Bangladesh.

a) Recovery Models: Faster and Slower Scenarios

Amount of 'n times processed' material recovered in Year, j :

$$R_{j,n} = 0.4\, R_{j-t,n-1} + 0.55\, R_{j-2t,n-1} \qquad \text{(Eqn. 6.2)}$$

where: j = current year

n = process number of materials recovered in Year, j

t = time step, where t = 1 year for faster scenario
t = 3 year for slower scenario

b) Landfilling Models: Faster and Slower Scenarios

Amount of 'n times processed' material landfilled in Year, j :

$$L_{j,n} = 0.02\, L_{j-t,n-1} + 0.03\, L_{j-2t,n-1} \qquad \text{(Eqn. 6.3)}$$

where: j = current year

n = process number of materials recovered in Year, j

t = time step, where t = 1 year for faster scenario
t = 3 year for slower scenario

c) Total amount of materials recovered or landfilled

Total amount of recovered materials present in the system in year, j :

$$\therefore \quad TR_j = \sum_{n=0}^{N} R_{j,\,n} \qquad \text{where } N = n - 1 \qquad \text{(Eqn. 6.4)}$$

[Since when $j = 1$, then $n = 0$;
similarly for $j = 2$, $n = 1$; $j = 3$, $n = 2$ ..... $j = j$, $n = j-1$]

Total amount of materials landfilled or taken off from the system in year, j :

$$\therefore \quad TL_j = \sum_{n=0}^{N} L_{j,\,n} \qquad \text{where } N = n - 1 \qquad \text{(Eqn. 6.5)}$$

6.4.2.2 Computer Programming

Considering the different rates and time steps of recovery and landfilling for different scenarios, all these above mathematical models were programmed separately and then combined together in FORTRAN computer language, in order to produce a single mathematical modelling programme. The programme developed is very fast in terms of time required to run the programme and get the results. It is also efficient as it requires a minimum level of manual intervention in changing the input parameters for getting alternative scenarios for plastic waste recycling, landfilling and trade-off between their recycling and landfilling. This trade-off is determined according to the legislative limit (hypothetical) in number of times of processing plastics successively. Such a limit may prevent recyclers recycling plastics after a certain number of successive processings. There are only four input variables need to be specified, depending on the desire of the future researcher or following the suggestions for further research: (a) amount of first virgin plastic imports; (b) number of years (i.e., next 10, 15 or 20 years) for which data are required; (c) rates of recovery or landfilling (e.g., 45% and 50% instead of 40% and 55%, respectively); and (d) length of time steps of recovery and landfilling which drives the system either as a slower or faster process (e.g., 2 year and 4 year time steps instead of 1 year and 3 year, respectively). More importantly, this

programme has the potential to link with some future dynamic planning and modelling, because each and every single input and output data of any kind used are stored in matrix form using multiple dimensions. For instance, a recovery output data itself can tell us about the materials: what is its year of recovery, how many times it has been processed, what is its path of recovery (either through 40% or 55%; whether it is a material that has been through faster or slower recycling systems). All this information has crucial importance not only for future planning and policy formulation purposes but to get a clear understanding of the materials' present quality by looking at its origin or path of its previous life-cycle(s).

However, it has been realised at this stage that there are some difficulties in tracking down through a series of model building concepts and mathematical equations, which were required: to elaborate enormous size of the system, and also to explain the methodology of computer programming to meet the modelling objectives (solving the problems, providing input data, and then generating and storing outputs/results in a readily available form for further use). By doing so and also to make the reading of this thesis more user-friendly, all these elaborations and mathematical equations/models developed are presented in Appendix 6.1, along with a number of useful diagrams.

Alternatively, attempts have been made to programme the same mathematical models (mentioned earlier) using EXCEL Spreadsheet and these are presented in Appendix 6.2. Obviously, this spreadsheet model is simple and relatively more understandable to those who are familiar with using any spreadsheet software package. However, this programme on spreadsheet is fast in generating output results, as is the FORTRAN programme. It is also efficient in getting results for different scenarios by changing input variables, i.e., rates of recovery/landfilling and length of time steps. Nevertheless, the user of this spreadsheet model must be aware about the following relevant issues:

- input and output data do not have any dimensional identity, always their values are required to refer to the corresponding column and row headings typed during the development of spreadsheet modelling;
- apart from changing input variables to obtain new scenarios, any extension of the spreadsheet programme beyond its designed ranges of rows and columns requires manual intervention (copying and pasting from and to the appropriate cell, respectively); and

- it is not straight forward to handle with the trade-off issues between amount of materials needing to be recycled and landfilled in response to any possible changes in the hypothetical legislative limit as defined before.

Anyway since both the techniques of modelling used are providing the same sets of results as discussed in the following sections, it is now reader's or future researcher's choice which way he/she need to go through to make the subject matters understandable and useful.

6.5 Results from Mathematical Modelling

6.5.1 Future Recovery Scenario Models

Table 6.1 summarises the basic findings obtained from the mathematical modelling of both the faster and slower recovery scenarios of Polyethylene (PE) imports, recovery and landfilling in Bangladesh for the years 1990-91 to 2004-05. Importation of PE, starting with an amount of 6.23 Mkg in 1990-91, rises to a seven fold higher amount of 35.35 Mkg in the year 2004-05. This rise in imports is same for both the faster and slower recovery models, but substantial differences have occurred in the cases of the values of recovery extended data points, recovery intercepts, and hence, the total amount present in the recycling system (Table 6.1).

For example, the total value of recovery extended data points in the year 2004-05 is 138.39 Mkg for the faster recovery model in comparison to 42.42 Mkg for the slower recovery model. Another major difference is observed in the case of the number of recovery intercepts. Although both the models start with no recovery intercept in the base year of 1990-91, the number of recovery intercepts grow to a large number (233) in the year 2002-03 under the faster recovery whereas this number is much lower (only 5) for the slower model (Table 6.1).

Table 6.1: Summary for **Faster** and **slower scenarios** of Polyethylene (LDPE and HDPE) **imports, recovery** and **total materials present** in their recycling system in Bangladesh, including **amount Landfilled** per year, 1990-91 to 2004-05. [In Mkg]

YEAR	FASTER RECOVERY					FASTER LAND-FILLING	SLOWER RECOVERY					SLOWER LAND-FILLING
	Imports [A]	Values of recovery extended data points [B]	Values of recovery intercepts [C]	*(Total number of recovery intercepts[1])*	**Total amount of materials present** [A+B+C]		Imports [A']	Values of recovery extended data points [B']	Values of recovery intercepts [C']	*(Total number of recovery intercepts[1])*	**Total amount of materials present** [A'+B'+C']	
1990-91	6.23	0	0	*(0)*	6.230	0	6.23	0	0	*(0)*	6.23	0
1991-92	8.31	0	2.49	*(1)*	10.80	0.125	8.31	0	0	*(0)*	8.31	0
1992-93	10.39	3.32	4.42	*(2)*	18.14	0.403	10.39	0	0	*(0)*	10.39	0
1993-94	12.47	10.06	3.14	*(3)*	25.67	0.687	12.47	0	2.49	*(1)*	14.96	0.125
1994-95	14.55	16.55	3.69	*(5)*	34.79	1.057	14.55	3.32	0	*(0)*	17.87	0.166
1995-96	16.63	24.83	3.20	*(8)*	44.66	1.466	16.63	4.16	0	*(0)*	20.79	0.208
1996-97	18.73	33.69	3.31	*(13)*	55.71	1.937	18.73	4.99	4.42	*(2)*	28.12	0.486
1997-98	20.79	43.76	3.09	*(21)*	67.68	2.454	20.79	11.72	0	*(0)*	32.51	0.607
1998-99	22.87	54.64	3.06	*(34)*	80.57	3.024	22.87	14.03	0	*(0)*	36.90	0.727
1999-00	24.95	66.51	2.92	*(55)*	94.38	3.641	24.95	16.34	3.14	*(3)*	44.43	1.011
2000-01	27.03	79.22	2.85	*(89)*	109.09	4.305	27.03	22.83	0	*(0)*	49.87	1.186
2001-02	29.11	92.80	2.74	*(144)*	124.66	5.013	29.11	26.19	0	*(0)*	55.30	1.362
2002-03	**31.19**	**107.20**	**2.66**	*(233)*	**141.05**	**5.766**	**31.19**	**29.55**	**3.69**	*(5)*	**64.43**	**1.732**
2003-04	33.27	122.41	2.57	*(377)*	158.25	6.561	33.27	37.83	0	*(0)*	71.10	1.973
2004-05	35.35	138.39	2.50	*(610)*	176.23	7.397	35.35	42.42	0	*(0)*	77.77	2.213

[1] Numbers in *Italic* font within first brackets show the total number of recovery intercepts in the year of recovery.

As a result, in the year 2002-03, the total amount of materials present in the system differs by about 80 Mkg between the two models. The differences in the 'number of intercepts' and 'amount of material present' in the two scenarios increases nonlinearly with increase of the number of years. This can be clearly seen in Figure 6.4. Table 6.1 and Figure 6.4 also show that the increase in the 'number of intercepts' and 'amount of materials' for each scenario follow a nonlinear pattern. Figure 6.5 shows the contribution of imports, recovery intercepts and extended data points to the total amount of material for the faster scenario.

As discussed earlier, the mathematical models (developed in this work) were also able to distinguish the amount of material according to the material's number of processings. For the faster recovery scenario, this is presented in Table 6.2 and Figure 6.6. It becomes apparent that new materials are recovered and recycled each year and they appear into the closed-loop recycling system with a new processing number. It is interesting to note from Table 6.2 and Figure 6.6 that processed zero (Pro-0) materials (6.23 Mkg) in 1990-91 becomes processed nine (Pro-9) materials (0.002 Mkg) in 1999-00. A much longer period is needed by the slower recovery model to reach this stage (in the year 2017-18 in Table 6.3). In other words, deterioration in the quality of the recycled plastic materials due to the effects of successive reprocessings and extraneous particles (added naturally from the system) will be delayed substantially, if materials are recovered and recycled following the slower recovery model developed on the basis of the longer life span of the plastic products.

Figure 6.4: **Scenario Models** for **Faster** and **Slower Recovery** of Polyethylene in Bangladesh, 1990-91 to 2004-05.

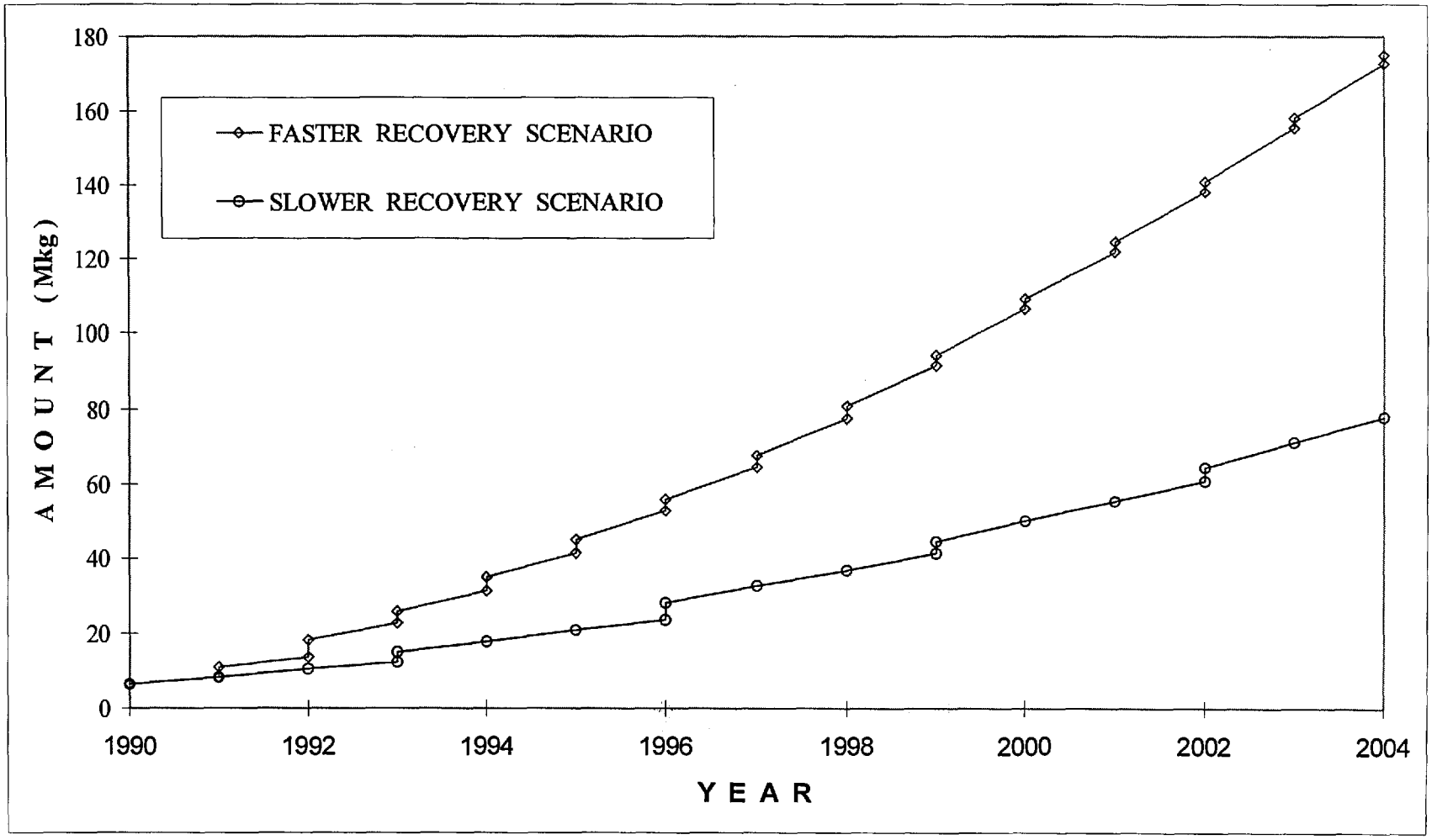


Figure 6.5: **Faster Recovery Model** of Polyethylene (LDPE and HDPE) **imports**, **recovery** and **total materials present** in the plastics recycling system in Bangladesh, 1990-91 to 1999-00.

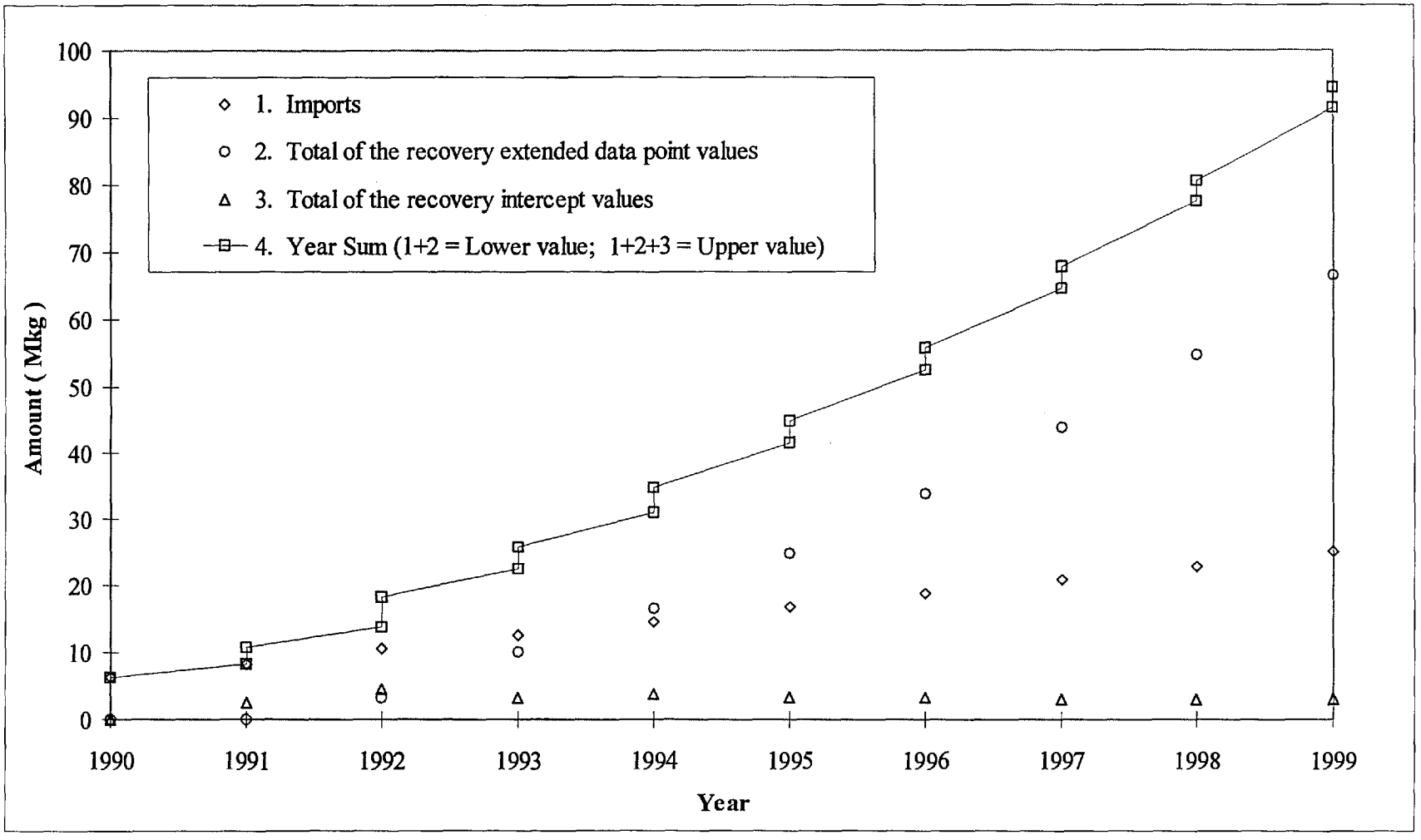


Table 6.2: Amount of Polyethylene (HDPE and LDPE) present in the plastics recycling system in Bangladesh, by their successive number of processings under the **faster recovery model.** [In Mkg].

Polyethylene by their successive number of processings	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Pro-0	6.23	8.31	10.39	12.47	14.55	16.63	18.71	20.79	22.87	24.95
Pro-1	0	2.49	6.75	8.73	10.70	12.68	14.65	16.63	18.61	20.58
Pro-2	0	0	1.00	4.07	7.20	9.08	10.96	12.83	14.71	16.59
Pro-3	0	0	0	0.40	2.18	5.12	7.59	9.38	11.16	12.94
Pro-4	0	0	0	0	0.16	1.09	3.25	5.85	7.93	9.62
Pro-5	0	0	0	0	0	0.06	0.52	1.90	4.13	6.39
Pro-6	0	0	0	0	0	0	0.03	0.24	1.05	2.69
Pro-7	0	0	0	0	0	0	0	0.01	0.13	0.55
Pro-8	0	0	0	0	0	0	0	0	0.004	0.05
Pro-9	0	0	0	0	0	0	0	0	0	**0.002**
Year total =	**6.23**	**10.80**	**18.14**	**25.67**	**34.79**	**44.66**	**55.71**	**67.64**	**80.567**	**94.38**

Figure 6.6: Graphical illustrations of the **different categories of Polyethylene** (HDPE and LDPE) present in the plastics recycling system by their successive number of processings under the **Faster Recovery Model**, 1990-91 to 1999-00.

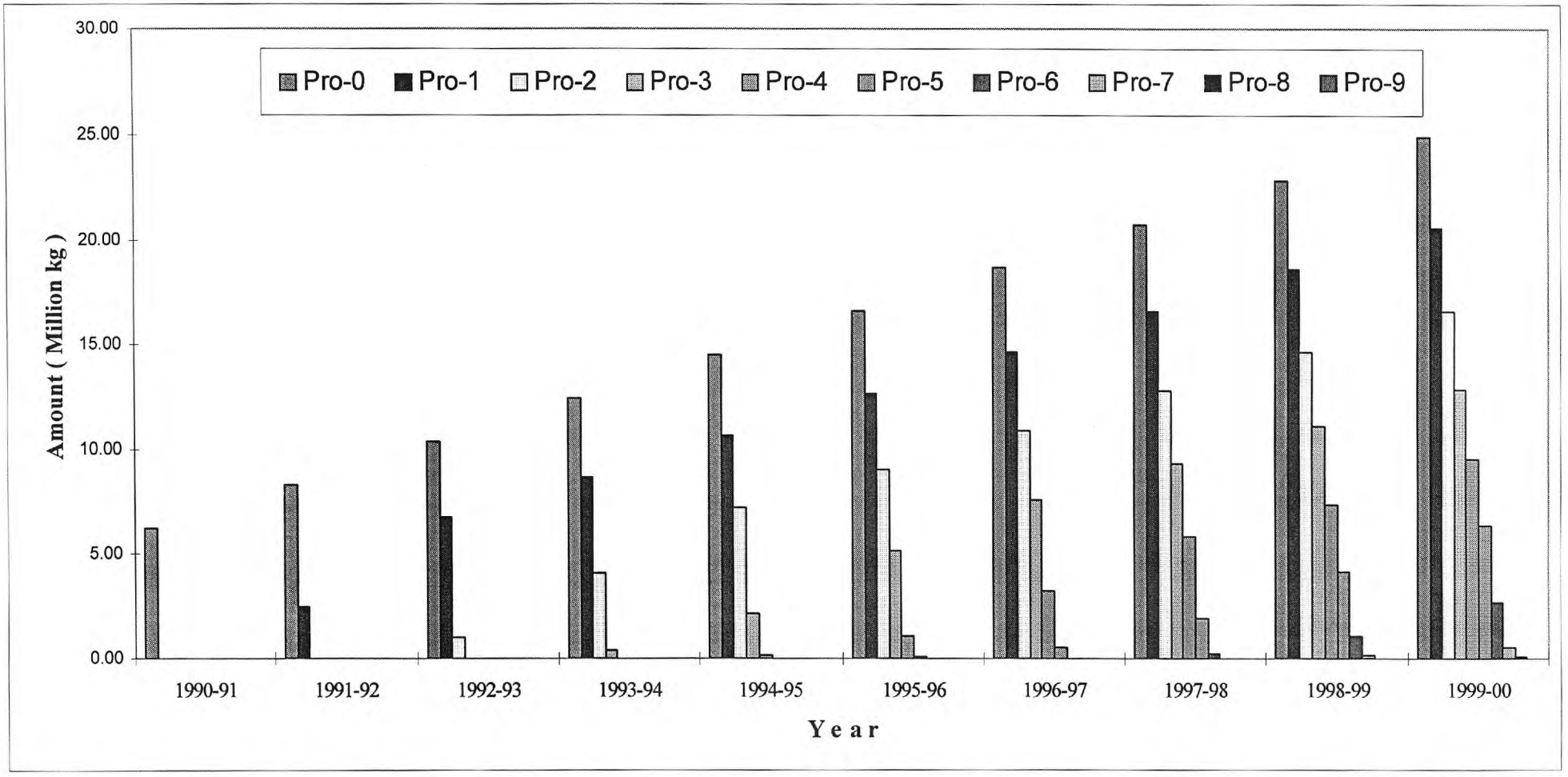


Table 6.3: Amounts of Polyethylene (PE) present in the system in Bangladesh during 1990-91 to 2017-18, **categorised** by their **successive number of processings** (SNP) according to the **Slower Recovery Model**. [In Mkg]

PE catego-rised by SNP	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01	2001-02	2002-03	2003-04
Pro-0	6.230	8.310	10.390	12.470	14.550	16.630	18.710	20.790	22.870	24.950	27.030	29.110	31.190	33.270
Pro-1	0	0	0	2.492	3.324	4.156	8.415	10.391	12.367	14.343	16.319	18.295	20.271	22.247
Pro-2	0	0	0	0	0	0	0.997	1.330	1.662	4.736	5.984	7.232	10.365	12.242
Pro-3	0	0	0	0	0	0	0	0	0	0.399	0.532	0.665	2.443	3.125
Pro-4	0	0	0	0	0	0	0	0	0	0	0	0	0.159	0.213
Pro-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pro-6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pro-7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pro-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pro-9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Year Total =	**6.230**	**8.310**	**10.390**	**14.962**	**17.874**	**20.786**	**28.121**	**32.510**	**36.899**	**44.428**	**49.865**	**55.302**	**64.428**	**71.096**

Continue ..... Table 6.3

PE catego-rised by SNP	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18
Pro-0	35.350	37.430	39.510	41.590	43.670	45.750	47.830	49.910	51.990	54.070	56.150	58.230	60.310	62.390
Pro-1	24.223	26.199	28.175	30.151	32.127	34.103	36.079	38.055	40.031	42.007	43.983	45.959	47.935	49.911
Pro-2	14.119	15.997	17.874	19.751	21.628	23.505	25.383	27.260	29.137	31.014	32.891	34.769	36.646	38.523
Pro-3	3.807	6.751	8.188	9.626	12.099	13.883	15.666	17.449	19.233	21.016	22.799	24.583	26.366	28.149
Pro-4	0.266	1.196	1.543	1.889	4.044	4.994	5.944	8.553	10.057	11.560	13.634	15.329	17.023	18.717
Pro-5	0	0.064	0.085	0.106	0.566	0.734	0.902	2.276	2.846	3.416	5.645	6.769	7.894	10.158
Pro-6	0	0	0	0	0.026	0.034	0.043	0.262	0.340	0.419	1.222	1.542	1.863	3.510
Pro-7	0	0	0	0	0	0	0	0.010	0.014	0.017	0.119	0.155	0.191	0.633
Pro-8	0	0	0	0	0	0	0	0	0	0	0.004	0.005	0.007	0.053
Pro-9	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002
Year Total =	**77.765**	**87.636**	**95.374**	**103.112**	**114.160**	**123.003**	**131.846**	**143.774**	**153.647**	**163.520**	**176.447**	**187.340**	**198.233**	**212.045**

6.5.2 Future Landfilling Scenario Models

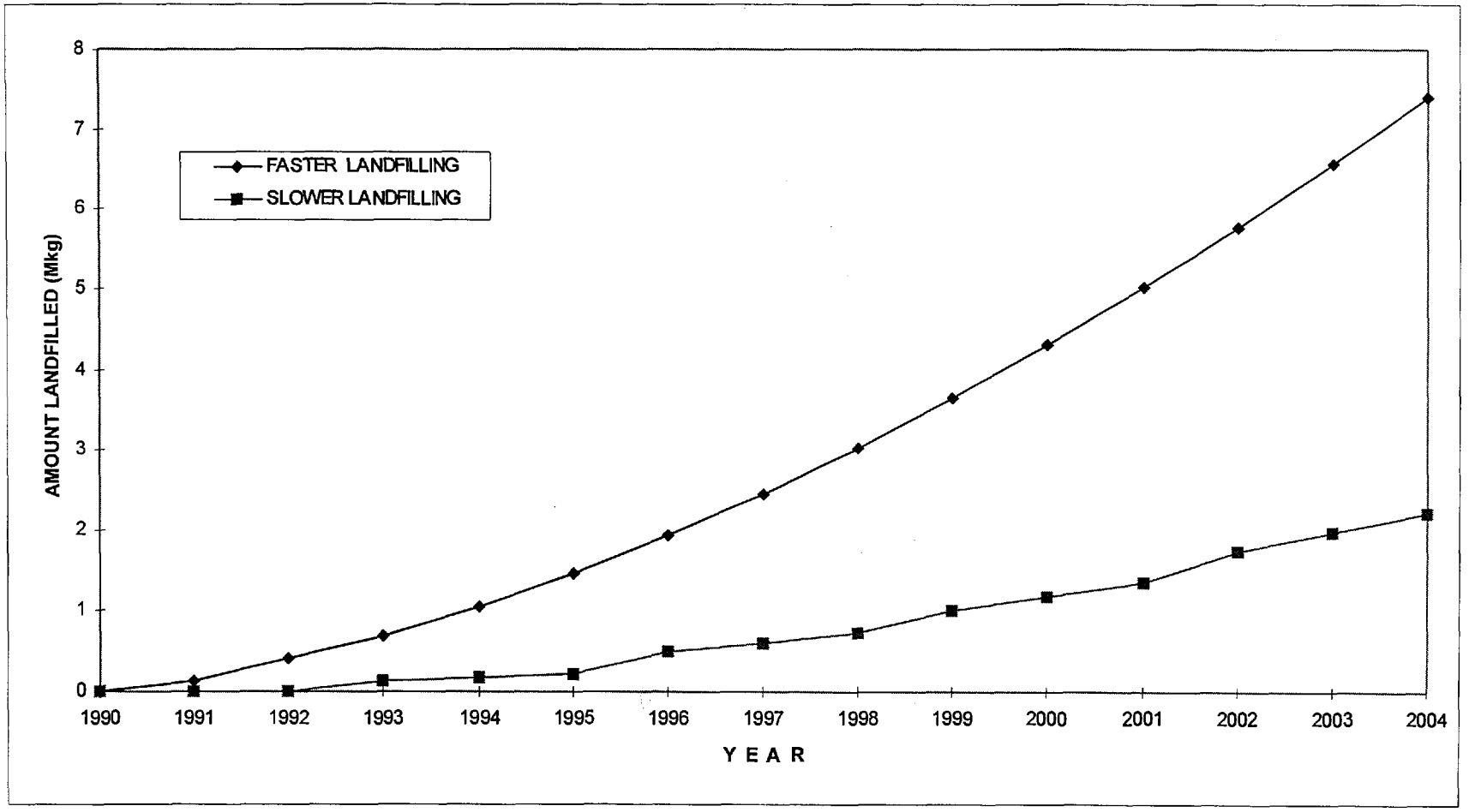
Taking into consideration the effects of the faster and slower recovery patterns, the amounts of materials landfilled also vary between the faster and slower landfill models (Figure 6.7). Like the slower recovery model, discarding used up products and hence landfilling the unrecoverable scraps portions take place after longer time steps due to considering their prolonged life span in the slower landfill model. Therefore, within the same length of time, a lower amount of discards is landfilled than the amount landfilled under the faster model. For example, a total of 7.4 Mkg and 2.2 Mkg of materials will be landfilled in the year of 2005-06, following the faster and slower landfill models, respectively (Table 6.1).

6.6 Quality Factors, Legislative Measures, and Other Scenarios

It has been clearly shown by the experimental results explained in Chapter 5 that a substantial degradation in both the mechanical and rheological properties is observed with successive processings of the HDPE general scraps collected from the plastic waste streams of Bangladesh and India. In particular, drastic falls in both their tensile strength and impact resistance performance occurred at around 5 or 6 number of times processed. This fall in mechanical properties is also supported by the steady increase in their melt flow rates. Even when a batch of virgin HDPE collected from Bangladesh has been successively processed up to 15 times under controlled conditions in London, a severe reduction in tensile strength after 4 times processing is indicated by the experimental results (Chapter 4). The results have also shown a decrease in impact resistance performance and a slight change in the rheological properties with increasing number of successive processings of the virgin material.

Therefore, if new legislative measures come into practice at some point in the near future which will eliminate recycling of the materials already processed more than 6 times (Legislative limit for number of successive processings, LgNSP > 6), as a consequence of concerns over deterioration, what would be the consequences for the plastics recycling scenarios of Bangladesh and India? What would be the changes in the amount of materials recovery and landfill?

Figure 6.7: **Scenario Models** for **Faster** and **Slower Landfilling** of Polyethylene in Bangladesh, 1990-2004.



These consequential impacts will occur first in those Polyethylene materials whose service life span is relatively short and successively processed following the faster recovery scenario. Accordingly, more materials will be landfilled within a shorter period of time. On the other hand, in the case of the slower scenario, the materials with a longer life span will take more time to be processed more than 6 times. Landfilling of the degraded materials will also start later.

Table 6.4 shows the variations in the findings obtained from the mathematical modelling as a result of addressing this hypothetical situation by incorporating a "quality factor" of recycled materials. Attempts have been made to assess the effect of legislative measures on the year sum of the amount of imports and recovery (Row C in the Table 6.4) present in the system, and also, on the year sum of the amount of landfilling (Row D) determined for each year, if the legislative measures result in no more recycling for the materials processed more than 6 times. It is postulated that if any lot of materials is taken out of the system and rendered useless due to legislative requirements, that amount would add to the existing amount of materials generally landfilled each year.

In this Table 6.4, values in 'bold' font show the results as obtained from the modelling. These values are also shown in 'normal' font, when no variation has occurred in their magnitudes due to the introduction of the hypothetical legislative measures. Only those values 'underlined' represent the extent of variations in the values (in bold font) due to the difference in the levels of the hypothetical legislative requirements.

Following the attempt, it is found that the year sums for imported and recovered materials during the years 1990-91 to 1996-97 (Row C) remain the same even after considering the legislative requirement of LgNSP>6 (Row C1), because these sums do not comprise any batches of material processed more than 6 times i.e. Pro-7, Pro-8, Pro-9 and Pro-10 materials. Therefore no changes occur during these years (1990-91 to 1996-97) in the year sum of the amounts landfilled (Row D and Row D1).

Table 6.4: The amount of Polyethylene present in the system and the amount landfilled if legislation is introduced to stop recycling of the recovered materials already processed 10, 9, 8, or 7 times, in Bangladesh. [In Mkg]

A	Years	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01	Comments
B	Type of materials by NTP present	Pro-0	Pro:0-1	Pro:0-2	Pro:0-3	Pro:0-4	Pro:0-5	Pro:0-6	Pro:0-7	Pro:0-8	Pro:0-9	Pro:0-10	
C	**Year sum for Imports (Pro-0) and recoverable (Pro-1 to Pro-10), [when no LgNSP exist]** (Data from Table 6.1 and 6.2)	**6.230**	**10.802**	**18.137**	**25.666**	**34.792**	**44.663**	**55.711**	**67.639**	**80.010**	**94.378**	**109.101**	
C1	Year sum - (Pro-7 to Pro-10), [when LgNSP>6]	6.230	10.802	18.137	25.666	34.792	44.663	55.711	67.629	79.881	93.773	107.148	
C2	Year sum - (Pro-8 to Pro-10), [when LgNSP>7]	6.230	10.802	18.137	25.666	34.792	44.663	55.711	67.639	80.006	94.326	108.793	
C3	Year sum - (Pro-9 to Pro-10), (when LgNSP>8)	6.230	10.802	18.137	25.666	34.792	44.663	55.711	67.639	80.010	94.376	109.080	
C4	Year sum - (Pro-10), (when LgNSP>9)	6.230	10.802	18.137	25.666	34.792	44.663	55.711	67.639	80.010	94.378	109.100	

D	**Year sum for general landfilling** (Data from Table 6.1)	**0.000**	**0.125**	**0.403**	**0.687**	**1.057**	**1.466**	**1.937**	**2.454**	**3.024**	**3.641**	**4.305**	Landfill may be increased by:
D1	Year Sum + (Pro-7 to Pro-10), [when LgNSP>6]	0.000	0.125	0.403	0.687	1.057	1.466	1.937	2.464	3.154	4.246	6.258	45.36%
D2	Year Sum + (Pro-8 to Pro-10), [when LgNSP>7]	0.000	0.125	0.403	0.687	1.057	1.466	1.937	2.454	3.028	3.693	4.613	7.15%
D3	Year Sum + (Pro-9 to Pro-10), [when LgNSP>8]	0.000	0.125	0.403	0.687	1.057	1.466	1.937	2.454	3.024	3.643	4.326	0.49%
D4	Year Sum + (Pro-10), [when LgNSP>9]	0.000	0.125	0.403	0.687	1.057	1.466	1.937	2.454	3.024	3.641	4.306	0.02%

Notes: (1) LgNSP = Legislative limit for number of successive processings beyond which no more recycling is permitted for the recovered materials with Pro-7, Pro-8, Pro-9 or Pro-10, if required by hypothetical legislative measures.

(2) Values in **'bold'** font: Results obtained from the modelling, considering no legislative requirements.

(3) Values in 'normal' font: No change occurred in the results obtained from the modelling, following the requirements of the hypothetical legislative measures proposed.

(4) Values 'underlined': New values appeared, following the requirements of the hypothetical legislative measures proposed.

During the year 1997-98 to 2000-01, changes due to LgNSP>6 occur in the sums of the materials present (Row C1) and landfilled (Row D1). For example, a total of 67.639 Mkg comprising 0 to 7 times processed materials are present in the year 1997-98 (Row C), and thus, this year sum is re-calculated as 67.629 Mkg after subtracting the 0.01 Mkg of 7 times processed materials (Row C1). At this year of 1997-98, as a result, a total of 2.454 Mkg year sum of landfilling (Row D) is added to by a total of 0.01 Mkg extra discards and gives a new year sum of landfilling of 2.464 Mkg (D1). Accordingly, this re-calculated sum of the materials present in the following years, 1998-99, 1999-00 and 2000-01, is determined by subtracting the corresponding total amount of 'Pro-7 to Pro-8', 'Pro-7 to Pro-9', and 'Pro-7 to Pro-10' materials, respectively (Row C1). New landfill year sums for these years (Row D1) are derived by adding these above subtracted amounts to their corresponding landfill year sums (Row D).

Another analysis has also been made in order to assess the changes in the amount of imports and recovery (Row C) and landfill (Row D), if a revision in the legislative measures results in no more recycling after 7, 8 or 9 times processing instead of 6 times (i.e. LgNSP>7, LgNSP>8, or LgNSP>9). If a revision in legislation requires that no more recycling occurs after 7, 8 or 9 passes, the reductions in the year sums of the total materials present in the system and hence addition of the equal amounts with the total amounts landfilled are shown clearly in Table 6.4, following the legislative requirements. It has been estimated that the amount of 4.31 Mkg landfill in the year 2000-01 may be increased by 45%, if a portion of the material present in the system needs to be discarded because of legislation prohibiting recycling of the materials which have already been processed more than 6 times.

If importation of virgin plastics into Bangladesh stops at some point in the future, the following will happen:

- both the virgin and recycled materials present at this point will go through an intensive system of recycling;
- then existing amounts of plastics will be diminished through successive intensive recycling and ultimately will be removed from the recycling loop, as the quality of recycled materials degrades with increasing number of successive recyclings and becomes seriously degraded, so that useless recycled plastics are landfilled;

- the time will come sooner in the case of the faster landfill scenario when there will be no plastics for recycling.

If a legislative measure is introduced in Bangladesh which stops all use of recycled plastics for producing commodity products based on health and safety grounds, then the following will happen:

- There will be a serious environmental risk if all existing recycled plastics are landfilled due to their potential energy which may cause landfill fire hazards. Moreover, in the long term plastics' additives may be released and contaminate severely land and underground water.
- or, these recycled materials will be stored for future alternative applications which require innovative ideas, techniques and equipment.
- a sudden rise in demand and importation of virgin plastic will occur even at its higher unit price;
- at the same time, use of substitute materials (e.g. jute, cotton, paper and glass products) will be increased to some extent to meet the demand from the markets.

6.7 Fitting the Model: General Discussion and Summary

These modelling exercises have described some aspects of behaviour of the recycling system being investigated. It is important to stress *some aspects* of the behaviour of the plastics recycling system in Bangladesh because developing these models is not an attempt at a complete description of the system, but only a description of the parts that have a major effect on the aspects under consideration. This is because of time constraints which have prevented all other attempts going further. For example, recyclability of plastic waste and marketability of the recycled products are closely associated with the socio-economic situation of the country. Nonetheless, these aspects could not be incorporated into the models for the time being, which could be done later. Therefore, these models are specific to the problem for which they have been constructed, and generally, if other information is required from these models then it will require modification.

Moreover, before any application of these models, the degree of uncertainty involved with the parameters of this mathematical modelling of plastics recycling must be evaluated. Generally, modelling parameters are evaluated from published data, or from experimental results of specific experiments designed to determine their value. In the case of the current models, a sensitivity analysis could have been done to assess the uncertainty associated with the nature of the imports trend lines shown in the Figure 6.1, to verify the level of fluctuation in the results obtained for the faster and slower recycling scenarios. This was not possible due to time constraints.

However, if the linearity in the imports trend becomes non-linear and this input parameter starts behaving differently, the mathematical models developed in this study will not be appropriate for application. In that case new mathematical models need to be developed with a different set of input parameters. Moreover, any change in the percentage proportion of recovery (40% or 55%) or any change in landfill proportions (2% and 3%) will also require the coefficients of the mathematical equations needed to be changed. It should be noted that these changes in the percentages are less contributory to the output parameters than any change in the input parameter of importation. Small changes in importation will cause a substantial change in the amount of materials recovered and landfilled. The reason is that changes in virgin plastics importation will bring *cumulative effects* on the recovery or landfilling scenarios, as the amount of plastics recovered or landfilled entirely depends on the amount of virgin plastics importation in to Bangladesh.

It is also important to assess the uncertainty related to one of the assumptions made for the purpose of modelling viz. that virgin plastics importation in Bangladesh started from 1990, and subsequently, recycling of discarded plastic articles also began. This assumption is clearly incorrect. Therefore, the situation will be complicated than the assumption here due to the fact that virgin pellets importation in the country started in 1960s, and also, due to the large amount of recyclates present in the system from earlier years. Moreover, the situation will be more complicated when questions arise about the practicality of some other assumptions. For example, here it has been assumed that there is no time gap between the stages of discarding-collecting-cleaning-processing-moulding-marketing, and recovery and landfilling time steps are fixed in time. In the case of plastics recycling in Bangladesh, it was observed during fieldwork that a period

of 3 to 6 months at the least is required for the discards to be recycled and marketed. Recovery and landfilling of the discards do not follow any particular 'time step' as assumed for modelling purposes.

Accordingly, if any discrepancies become evident from the sensitivity analysis, these models may require revision of the original assumptions and modification of some of the equations developed, in an attempt to improve the agreement between assessment results and the models. Once the parameter fitting stage is over, and the limits of the accuracy of the models are known, then the models will be ready for use.

CHAPTER 7:

Plastics Recycling Scenarios in Developed Economy: The UK Case Study

7.1 Introduction

The environmental impact of plastic waste disposal is a problem of high priority in most industrialised countries. This is mainly due to a build-up of this recyclable waste in landfills, and due to campaigns and opinions from public and media, focusing on this issue. In most of the Western European countries, plastics' proportion in landfills is less than 10% but public attention to them is increasing. A possible reason for such a reaction is incompatibility of plastics with the environment. Figure 7.1 shows all different socio-economic, human, environmental and legislative factors governing, and more specifically, preventing the growth of plastic waste recycling in the cities of advanced countries which have developed on the basis of economics, environmental concerns and legislation. This has been developed in the present study from literature research performed and presented in this chapter, and also, in Chapter 2.

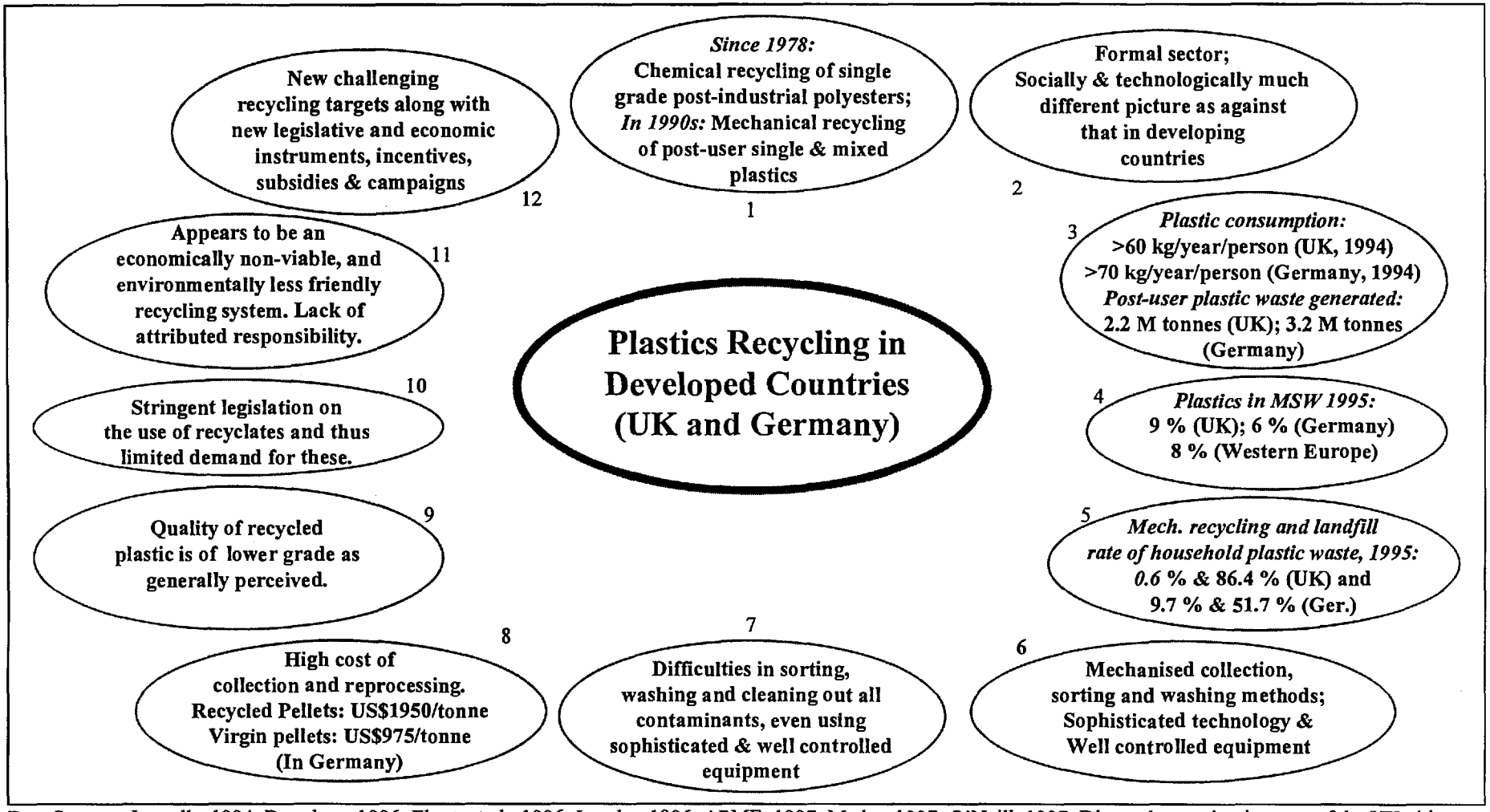
Recyclers in developing countries such as Bangladesh and India are facing difficulties in recycling PET waste due to a lack of necessary technology and knowledge. In contrast, in the developed countries, particularly in the USA, Germany, the UK and Ireland, PET is recycled in reasonably large amounts because of its suitability for recycling and availability of technology required (Simonian, 1995; Winter, 1993).

7.2 Current Rate of Generation and Recycling

Table 7.1 shows the UK's plastics consumption and waste generation scenarios in 1995, a total of 2.2 million tonnes of post-user plastic waste was generated against its consumption of 3.3 M tonnes (APME, 1997). Of the total post-user waste 64 % is packaging waste. Figure 7.2 illustrates that the household sector dominates all other sectors.

Table 7.2 indicates that a total of 91.4 % of post-user plastics waste is disposed of without any recycling. Household plastic waste accounts for 4% of the total MSW and 8.5 % of the total household waste (Table 7.3). The mechanical recycling rate for household plastics waste is only 0.6 % in the UK, compared to 9.7 % mechanical recycling and further 5.6 % feedstock recycling in Germany (Table 7.4)

Figure 7.1: Socio-economic, human, environmental and legislative factors governing plastic waste recycling in the cities of the developed economy.



Data Sources: Lascells, 1994; Brandrup, 1996; Ebert, et al., 1996; Luesby, 1996; APME, 1997; Mader, 1997; O'Neill, 1997; Direct observation in some of the UK cities, 1994-1998.

Table 7.1: Scenario of Plastics **Consumption** and **Waste Generation** in the UK compared with some other Western European countries, 1995 (Units: x 1,000 tonnes /year).

Country	Popu-lation (x 1,000)	Consumption					Post-user plastic waste generation					
		Final consumption of all plastics	Change in plastic processors' consumption (% 1995 / 1994)	Final consumption of plastic packaging			Total	Packaging waste	Household plastic waste			
				Total	Household (% of the total)	Industry / Distribution (% to the total)			Total	of which packaging		
							(A)	(B)	(C)	Total	% to total household plastic-[C]	% to total post-user packaging-[B]
UK	58,295	3,302	+0.7	1,519	73 %	27 %	2,193	1,395	1,300	1,049	81 %	75 %
Italy	58,261	3,900	+ 2.5	1,747	79 %	21 %	2,450	1,608	1,641	1,297	79 %	81 %
France	58,109	3,546	- 2.9	1,690	77 %	23 %	2,997	1,555	2,041	1,219	60 %	78 %
Germany	81,337	5,998	- 1.1	1,695	62 %	38 %	3,181	1,547	1,799	984	55 %	64 %

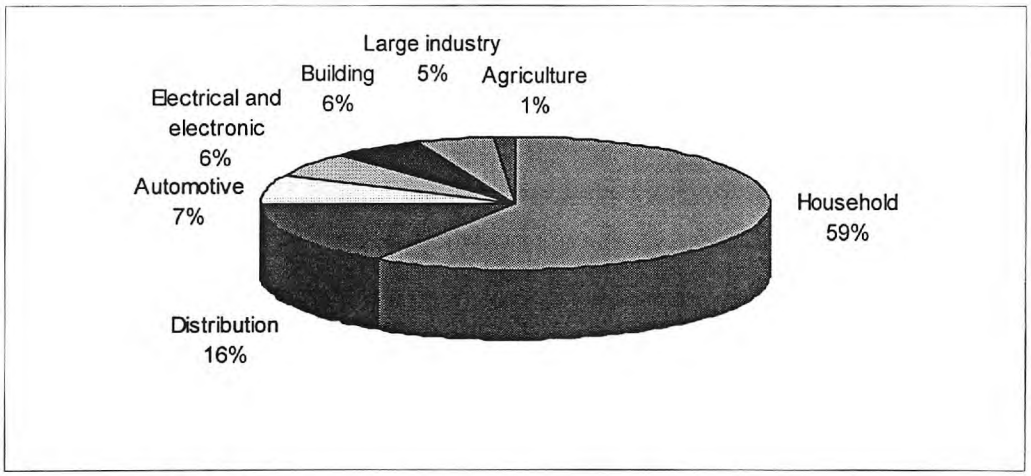
Data source: APME, 1997.

Table 7.2: **Management** of **post-user** plastic waste by end-use sector in the UK, 1995.

End-use sectors	**Households**	**Distribution & Large Industry**	**Agriculture**	**Automotive**	**Other**	**Total**
Waste generated (ktonnes / year)	1,299 (100 %)	453 (100 %)	33 (100 %)	153 (100 %)	255 (100 %)	2,193 (100 %)
Mechanical recycling	0.6 %	16.0 %	16 %	5.9 %	--	4.6 %
Feedstock recycling	0.0 %	0.0 %	0 %	0.0 %	--	0 %
Energy recovery	5.0 %	3.0 %	--	--	--	4 %
Incineration without energy recovery	8.0 %	2.0 %	--	--	--	91.4 %
Landfill	86.4 %	79.0 %	--	--	--	

Note: "--" Data not available. Data Source: APME, 1997.

Figure 7.2: Post-user plastic waste generation by end-use sector in the UK.



Data Source: APME,1997.

Table 7.3: **Plastics in** the Municipal Solid Waste (**MSW**) by source in the UK, 1995.

	MSW (All materials)				
	Total MSW	of which household	Plastics in MSW		
			Household	Non-household	Total plastics
Amount (ktonnes)	32,512	15,240	1,300	1,472	2,772
% to MSW	100 %	47 %	4.0 %	4.5 %	8.5 %
% to all household waste materials	N.A.	N.A.	8.5 %	N.A.	N.A.

Data Source: APME,1997.

Table 7.4: **Household** plastic waste **management** by country and management method, 1995.

Waste Management Options		**UK**	**Germany**	**Denmark**	**Switzerland**
Household plastic waste (ktonnes / year)		1,299	1,799	99	226
No Recycling	Landfill	86.4%	51.7%	19.0%	13.8%
	Incineration	8.0%	0.0%	0.0%	16.0%
Incineration with energy recovery		5.0%	33.0%	80.0%	64.0%
Mechanical Recycling		0.6%	9.7%	1.0%	6.2%
Feedstock Recycling		0.0%	5.6%	0.0%	0.0%

Data Sources: APME, 1997.

Table 7.5 shows that the UK recycled locally only 0.7 % (using mechanical method) of household plastic packaging waste in 1995 compared to 28 % in Germany (using both mechanical and feedstocks recycling methods). This percentage accounts 1.6 % in Italy and 1.2 % in France. Of the total amount of plastic packaging wastes from the industry

Table 7.5: Scenario of **post-user plastic packaging waste management** by end-use sectors in the UK compared to some other Western European countries, 1995.

Country	From Household Sector				From Industry / Distribution Sector			
	Total amount (x 1,000 tonnes /year)	Mechanical and Feedstock Recycling			Total amount (x 1,000 tonnes /year)	Mechanical and Feedstock Recycling		
		Recycled within the country*	Export outside Europe to be recycled	Rate		Recycled within the country*	Export outside Europe to be recycled	Rate
UK	1,049	0.7 %	0.1 %	0.8 %	347	20.8 %	2.9 %	23.8 %
Italy	1,297	1.6 %	0.2 %	1.8 %	311	23.2 %	5.8 %	29.2 %
France	1,219	1.2 %	0.3 %	1.5 %	335	29.0 %	9.6 %	38.3 %
Germany	984	28.0 %[#]	24.0 %	52.1 %	564	23.8 %	4.4 %	28.3 %

Notes: *Without intra European import; [#]Including feedstock recycling because only Germany in WE operates this method of recycling.
Data source: APME, 1997.

and distribution sectors in 1995, the UK recycled locally 20.8 % compared to 23.8 % which is accounted for by Germany. In the case of exporting household packaging wastes outside Europe, Germany (24.0 %) is much above its European counterparts (UK-0.1 %; France-0.2 %; and Italy-0.3 %). All these four countries also exported 3-10 % of their plastic packaging wastes collected from their industry and distribution sectors as shown in Table 7.5. All these facts indicate that plastic packaging wastes are less suitable for recycling in the developed countries. As a result, a major portion of the post-user plastics wastes is destined to end up in landfilling (Tables 7.2 and 7.4) and another proportion of the waste has found its way to export outside Europe (Table 7.5) due to the underlying barriers in plastics recycling in these countries as discussed in the following sections, mainly from a UK perspective.

7.3 Existing Barriers in Plastics Recycling

7. 3.1 Economic Barriers

Cost of recycling, particularly the cost of reprocessing is identified as the main barrier to the development of the post-consumer plastics recycling in the UK (Waite, 1995). Post-consumer plastics are a mix of their different polymeric types and contaminated through contact with the product which they have been used to package and through contact with other materials during collection. All different types of plastics need to be separated prior to their processing. Unwanted contaminants either polymeric or non polymeric, must also be removed through washing and further separation processes. In particular, washing plastic feedstocks is expensive. Very few companies in the UK have invested in washing equipment and thus the market demand for post-consumer plastics is small (Waite, 1995). However, both separation and washing add to costs of reprocessing the waste.

In Western Europe (WE), the total consumption of plastics in 1995 was 24.7 M tonnes, of which 41 % and 59 % were used by the packaging and non-packaging sector, respectively (APME, 1997). Out of the post-user plastic waste generated in this region in the same year, 57 % was packaging waste and the rest 43 % was non-packaging waste (APME, 1997). According to the view expressed by Nancy Russotto, director of APME

during 1991, it was believed that *"to recycle 60 per cent of household waste Europe will have to spend 20 bn Ecu or £14 bn* (US$ 21.8 bn) *on centres to process waste packaging alone"* (Bell, 1991). Considering the present amount of packaging waste generation, this cost will be much higher than the cost as envisaged on the basis of the situation at the beginning of the 1990s.

A second limiting factor of plastics processing is the cost of transporting these very light materials which must be baled in order to achieve a reasonable payload on a delivery vehicle. This transport cost must be exacerbated if these materials are required to be transported a long way, in order to deliver these to one of the few plants capable of processing such material in the UK (Waite, 1995).

Thirdly, although the economics of plastics recycling are slowly improving, the economics of plastics collection for local authorities remains negative (ENDS Report 245, 1995). It is also mentioned in the report that the price paid for PET by RECOUP (Recycling of Used Plastic Ltd) has risen from £120 per tonne in 1994 to £200 per tonne in 1995, and this increase has been from £75 to £120 per tonne for HDPE. Although the cost of plastics collection is still high, there has been an improvement from a deficit of £300 per tonne to about £180 per tonne in 1995 (ENDS Report 245, 1995). This figure could be cut down when it is coupled with recycling credits, which could make plastic recycling more attractive.

7.3.2 Social Barriers

Social barriers in the expansion of the market for recycled plastics are well documented in a recently published book (Waite, 1995). Consumers' attitude about, and acceptability to, recycled products are the important barriers in increasing its wider applications. In this respect, other key aspects are consumers' misconceptions, prejudices and a lack of understanding about the performance of recycled products. In most of the cases the word 'recycled' gives impression of something which is inferior in quality.

Inappropriate, unnecessary tight or over-specified standards/specifications set for recycled products by the authority concerned also cause indirect resistance in expansion of the use of recycled products. For example, there is a specification which requires that *"fence posts*

must be made of wood" and therefore, application of recycled plastic products for this purpose is excluded, even though recycled plastic fence may in fact be technically superior and more durable (Waite, 1995).

7.3.3 Technical Barriers

a) In sorting plastics

Problems associated with plastics sorting using 'plastic coding system' and 'automated sorting techniques' have already been discussed in Chapter 2. This section includes some more relevant issues mainly associated with mechanical recycling of the waste. Until recently, large scale mechanical recycling of plastic waste in the UK was difficult to achieve due to the lack of necessary sorting techniques and infrastructure. Problems and complexities increase when mixed plastics are recycled together which give inconsistent and unpredictable quality for recycled products (Cooper, 1994). Sorting problems remain with the quality of the plastics processed different numbers of times. Plastic, even when pure, cannot behave like glass or metal, which does not weaken in terms of quality when they are melted and reformed; whereas plastics may degrade when processed and could become inferior to virgin plastics (Luesby 1996), although present work shows that properties of HDPE do not change significantly until 4-6 numbers of successive processings.

It can even be difficult to recycle plastics when a particular type of polymer has different type of fillers and additives (Cooper, 1994; Sarson, 1992). It has also been noted in the literature that depending on the type and concentration of a particular pigment, polymer properties degrade at different rates (Williams & Bevis, 1980a). This variation may also produce heterogeneous characteristics within the same type of plastic, which can enhance the current level of difficulties in plastics sorting.

b) In removing impurities

Waste plastics reclaimed from domestic sources are mostly impure and dirty and thus without prior reprocessing these cannot be fed directly into the production process to produce finished products. The existing sorting, cleaning and refining technologies, in the UK and most developed countries, can remove efficiently many of the contaminants. At

the same time, these reprocessing technologies have a number of limitations on the removal of some contaminants, particularly if they are chemically or physically bound into the structure of the waste plastic (DoE, 1991). For example, it is very difficult at the moment to remove adhesives which are physically attached to the surface of plastic. Therefore, there are growing interests into the problems of adhesives in affecting the quality of recycled plastic (Bell, 1995). These are increasingly used to stick paper labels on plastic products and also to stick different types of plastic together. Some other problems in mechanical recycling resulted from the effects of contaminants and successive processings on the properties of plastics have already been elaborated in section 2.3.1.5 in Chapter 2. However, an in-depth analysis of the issues related to the effects of successive processings on polymer properties is made on the basis of literature research and presented in the following sections.

7.4 Effects of Successive Reprocessings

7.4.1 Effects on Tensile Properties

It has been mentioned in Chapter 2 that Williams and Bevis (1980a, 1980b, 1981 and 1982) carried out an in-depth study in the UK to determine the properties of *virgin polypropylene co-polymer* in association with the effect of incorporating an increasing proportion of the recycled materials after each of the six runs of its successive injection-moulding. Test specimens were prepared from 3 mm plaque moulds produced from feedstocks containing 0%, 10%, 20%, 50% and 100% of the materials recycled (i.e. processed) once to four times. It was found in their study that, in the cases of the specimens containing 100% of material recycled up to four times, stress at yield and stress at break properties were slightly changed from the corresponding values of the virgin material (Williams and Bevis, 1980b). However, a significant decrease in the strain at break from 5.68 mm/mm to 2.05 mm/mm occurred with an increase in the number of passes, as reported by them.

Ram and Getz (1984) have found a change in the opposite direction- the ductility (strain at break) of *recycled* LDPE is moderately increased due to the shearing effect of successive injection mouldings.

7.4.2 Effects on Impact Resistance

The results obtained by Williams and Bevis (1980b) revealed that, in the case of 3 mm plaque mouldings, incorporation of 100% recycled twice material caused a deleterious effects on impact strengths of the plaques, and their impact performance were affected much seriously when 100% of thrice and four times recycled materials were incorporated. In their study, in the case of the 6 mm plaque mouldings, there was little deterioration in the impact performance (measured two weeks after moulding) with increasing percentage of recycled once material.

7.4.3 Effects on Melt Flow Rates (MFR) and Gel Contents

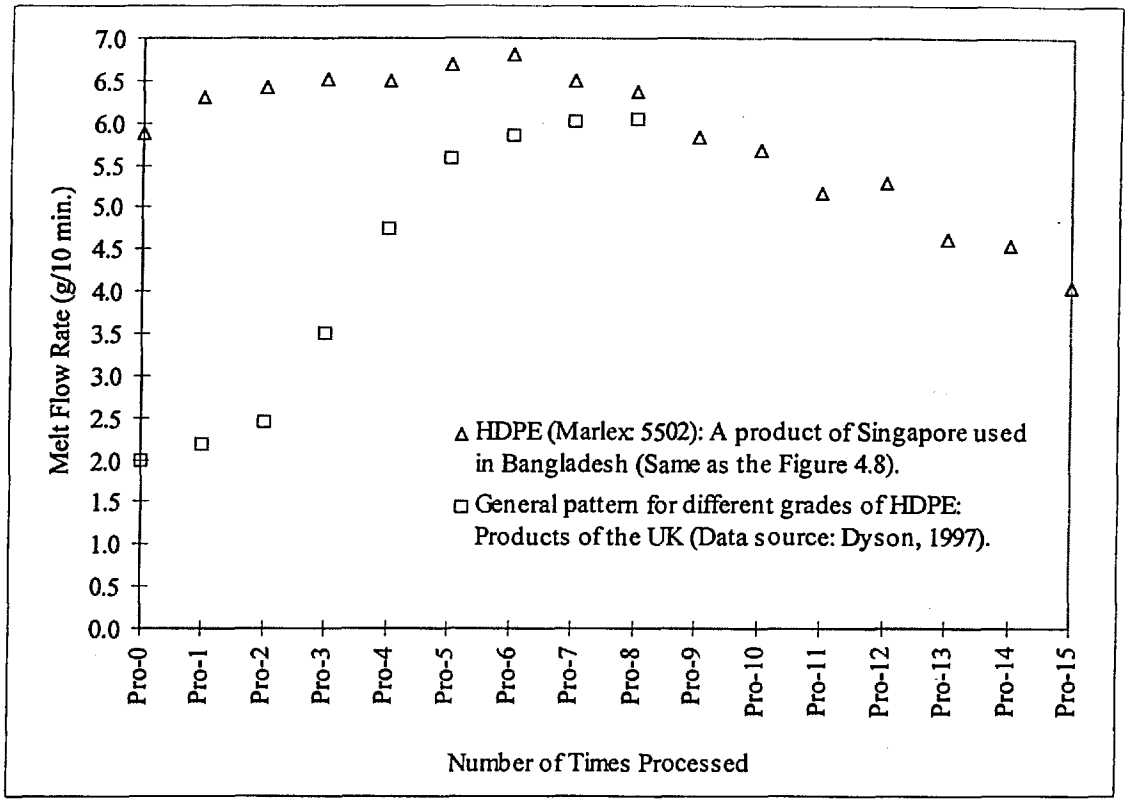
a) For virgin plastics

Increase in MFR with the increase in process number - virgin plastics: Williams and Bevis (1980b) found a marked increase in MFR (4.5g to 7.5g per 10 min) and accordingly a decrease in average molecular weight ($6.33x10^4$ to $2.53x10^4$) with the increasing number of successive *injection mouldings* of *virgin polypropylene co-polymer* up to four times. Similarly, their results obtained from another experiment indicated that an increase in MFR (5.6g to 10.9g per 10 min) occurred when the material was *extruded* repeatedly up to six times. Their results also revealed that a reduction in molecular weight from the incorporation of recycled material in the feedstock led to more efficient transmission of pressure by the melt and thus a reduction in the melting point of the material employed.

Frequently, it has also been observed by Dyson (1997) that MFR values of different grades of HDPE produced in the UK initially increase for their 3-6 process number and then level off with the higher number of processings up to 7-8 times (Figure 7.3). However, in the case of the present study which is dealing with the HDPE produced in Singapore which is being used in Bangladesh, it has already been mentioned in Chapter 4 that MFR of material (Singapore) has initially increased up to Pro-6 and then decreased until Pro-15. If the former materials (Dyson, 1997) could have been processed beyond 7-8 times, the trend of their MFR values might not remain constant, and could have been decreasing or increasing. However, the reasons for these contrasting sets of MFR results observed in their changing pattern over successive

reprocessing steps are unknown. It may be due to the fact that MFR test itself is a crude method of test (Dyson, 1997). Besides, if this is not the case, the variation might due to the differences in their inherent properties as these materials were produced by two different manufacturing processes involved in their country of origin.

Figure 7.3: Variations in the effect of successive processing on MFR of virgin HDPE produced by different manufacturing processes.



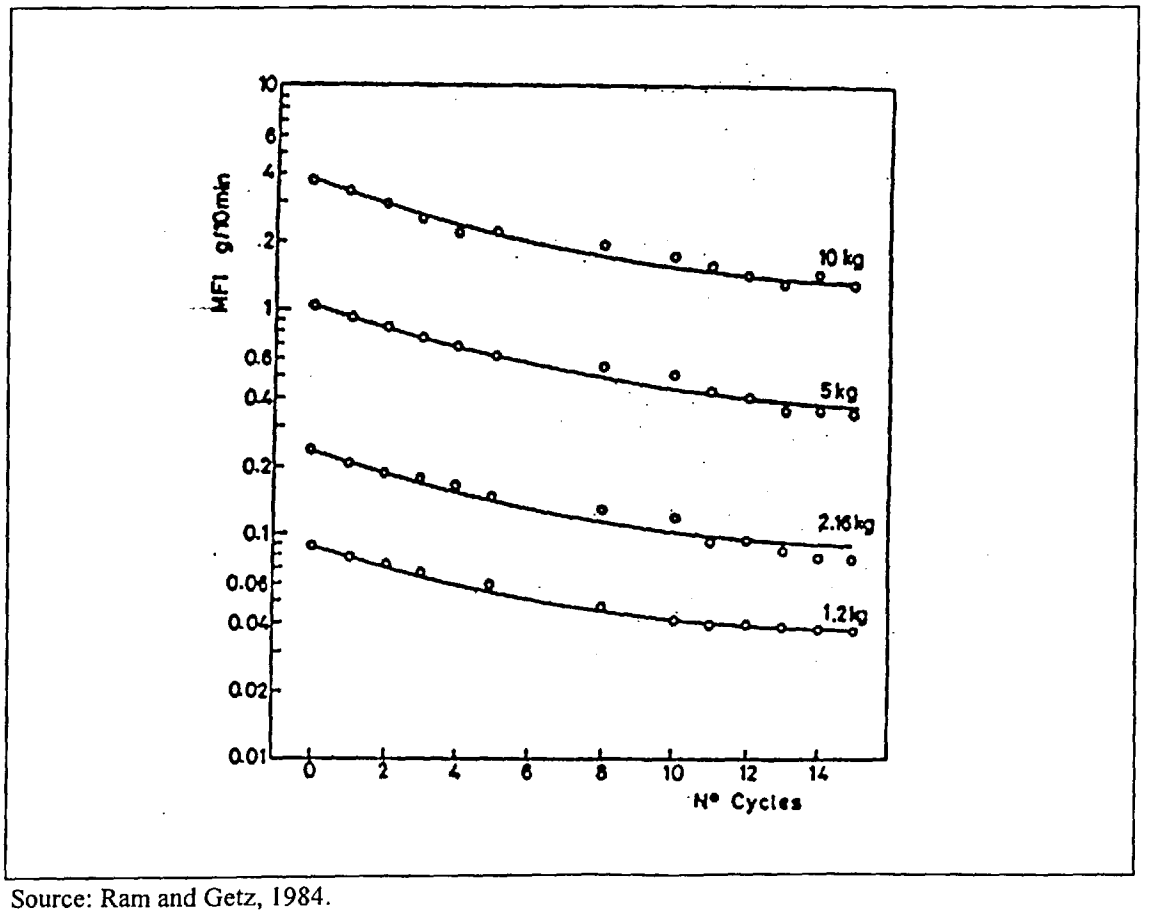
Note: See Chapter 4 for Figure 4.8.

Decrease in MFR with the increase in process number - virgin plastics: In contrast, although increase in molecular mass and thus decrease in MFR are not likely to happen generally, it may only be possible in those cases where *cross-linking* or a *reversible process of disentanglement* of polymer chains occur during reprocessing. It is interesting to note that there are some earlier studies which reported this decrease in MFR for LDPE and HDPE (in below).

Ram and Getz (1984) have attempted to explore ways to improve flow and product performance by intensive shear processing. They have reprocessed both the reclaimed and virgin LDPE up to 15 times, using a injection moulding machine. Their paper has reported that processing of a virgin polymer caused degradation by thermal and

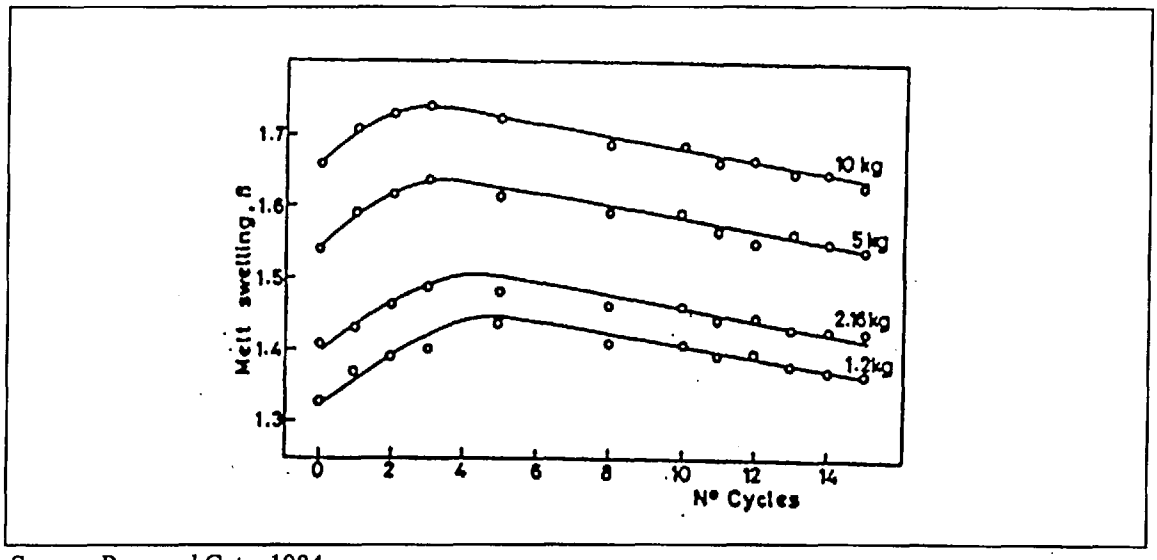
mechanical effects which entails an increase in molecular weight and a decrease in MFR through recombining free-radical chains and forming microgel structure. In their study, MFR values of the virgin LDPE have been measured, using four different loads of 10, 5, 2.16, and 1.2 kg, against their number of successive injection mouldings (Figure 7.4). They have come to the same conclusion for each of the four different loads used, viz. that the MFR value progressively decreases for increasing numbers of injection mouldings. They have also measured melt swell ratio (puff-up ratio), a criterion for melt elasticity calculated as the ratio between the diameter of extrudate and that of the die fitted on MFR test machine, of LDPE. In their experimental results, they have found that the swell ratio of the virgin LDPE against number of successive injection mouldings initially increases up to a maximum, around four times moulding and then decreases (Figure 7.5). These trends in the MFR and melt swelling ratio (Ram and Getz, 1984) are in general agreement with the MFR results obtained in the present study, with the initial increase and then decreasing trend as shown in Figure 4.8 (in Chapter 4).

Figure 7.4: Effect of injection moulding on MFR of virgin LDPE.



Source: Ram and Getz, 1984.

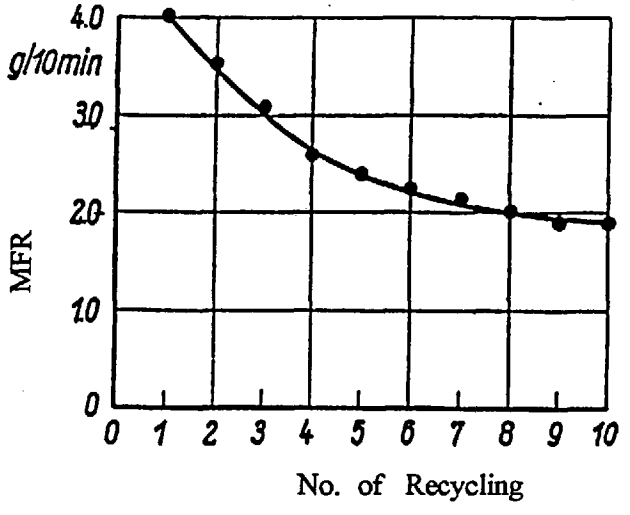
Figure 7.5: Effect of injection moulding on melt swell of virgin LDPE.



Source: Ram and Getz, 1984.

Decreasing trend in MFR over the several recyclings of HDPE has also been demonstrated in another study carried out by Beizaie and Zaidi (1974) as shown in Figure 7.6.

Figure 7.6: Melt flow rate of HDPE measured after different number of processing.



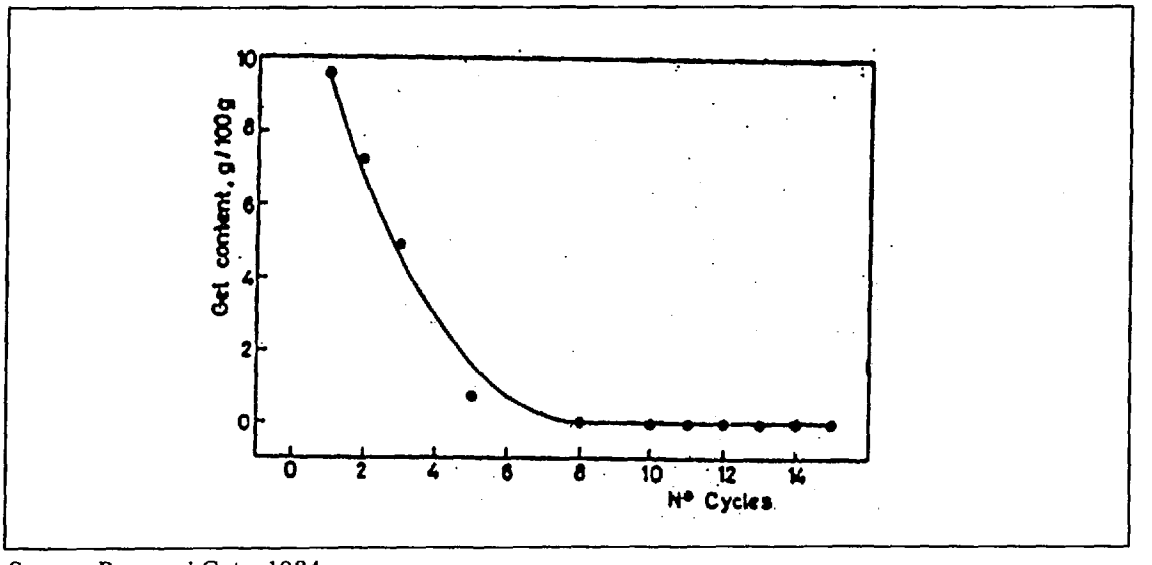
Source: Beizaie and Zaidi, 1974.

However, the specific reason for the discrepancy between increasing and decreasing trend of MFR at any stage of successive processing *virgin PE* remains unknown, which needs further investigation. In summary, it has become apparent that, depending on the tensile strength and MFR test results obtained in this study and those reported in the previous studies/literature, a substantial change occurs in the properties of *virgin PE* after 4 times of successive processings. Therefore, the unsolved questions after 4/5 times of reprocessing require further work to be carried out.

b) Recycled plastics

For *recycled* LDPE, a steady increase in MFR value of with increasing 'duration of shearing' during extrusion has also been found by Ram and Getz (1984). They mentioned in their experiment, that the reclaimed polymer, which was partly crosslinked, experienced mastication effects during successive injection mouldings, resulting in a gradual breakdown of gel contents and thus an enhancement of MFR. On the basis of another set of their experimental results, they have found a steady decrease in the *gel contents* of reclaimed LDPE which then levelled off from 8th cycle due to the shearing effects with 15 cycles of injection moulding (Figure 7.7).

Figure 7.7: Effect of injection moulding on gel contents in reclaimed Low Density Polyethylene (LDPE).



Source: Ram and Getz, 1984.

7.4.4 Effects on Apparent Viscosity

Ram and Getz (1984) have found an increase in apparent viscosity while virgin LDPE was injection moulded up to 15 times. One possible explanation for this increase in the viscosity over the course of fifteen times of processing could be due to 'crosslinking' or 'disentanglement' effects which may be caused by oxidation or mechanico-chemical processes (Brydson, 1981; Ram and Getz, 1984, BSI, 1995; Williamson, 1997).

7.4.5 Effects of Colour Pigments and Weathering

Williams and Bevis (1980a, 1980b, 1981, 1982) evaluated the effect of compound additive and weathering upon the properties of virgin polypropylene co-polymer. In these cases the feedstocks were also prepared by mixing 0%, 10%, 20%, 50% and 100% of recycled materials.

a) Effects of pigments on impact strength

Williams and Bevis (1981) investigated the effects of increasing concentration of three different pigments - carbon black, ultramarine blue and phthalocyanine blue - on the impact properties of one grade of an injection moulded virgin polypropylene co-polymer. They observed a decrease in impact strength of the injection moulded plaques with increasing concentration of any of these three pigments incorporated at the level of 0.1% to 2.0%. Carbon black was followed by ultramarine blue and then by phthalocyanine blue in causing less deleterious effects upon the impact strength of the plaques. They noted that impact strength property was less affected by the incorporation of the recycled material compared with the effect of the pigments.

b) Effects of Weathering

Walker (1995) defined 'weathering' as a gradual process by which materials on the external faces of products are affected by natural climatic condition but this effect varies regionally. He added that the effects of weathering are partly mechanical and partly

chemical. Along with the mechanical and thermal effects during reprocessings, 'weathering' also plays an important role in affecting the polymer qualities. Since investigation to determine the effects of weathering was not covered within the scope of the present study, relevant results are reviewed here from previous work. Possible reasons for change in polymer properties due to weathering effects have been described by Williams and Bevis (1980a). They considered that processing a polymer may lead to molecular degradation and loss of additives, resulting in an increase in free radicals and active chain ends, and thus, recycled plastic products may be more susceptible to weathering effects than the products produced from virgin materials.

In their study (Williams and Bevis, 1980a and 1980b), the impact strength was determined of 6 mm thick polypropylene co-polymer plaques after different lengths of time under artificial weathering effects. The plaques, which incorporated with no pigment but various percentages of recycled materials, were exposed under a 'kW carbon arc' of a Marr weathering machine. They found after a total of 1162 hours of artificial weathering, which is approximately equivalent of one year of natural weathering, *"impact strength of the plaques increased up to 50% level of recycled material content, and then dropped down to the lowest recorded value for 100% recycled material"* (Williams and Bevis, 1980b). Their results also showed that weathered plaques suffered from lower impact strength than the corresponding value of un-weathered plaques. It is important to note that, in their study, the virgin plaques and those containing 100% recycled material both experienced similar weathering characteristics but their impact strength dropped by 14.3 Joules and 15.3 Joules, respectively. This means that the effect of weathering is almost same on both the virgin and recycled co-polymer. According to another set of results obtained for the virgin plaques, an increase in impact performance occurred, rising from 43.1 Joules at two weeks after moulding to 49.0 Joules after storage for one year in the absence of ultra-violet light (which is one of the major factors in causing weathering effects on plastic).

Finally, according to the concluding remarks made by Williams and Bevis (1982), polymer properties, particularly impact strength and microstructure, can be affected substantially by incorporation of pigments, ultra-violate stabiliser and recycled material.

7.5 Overall Status of the UK Plastics Recycling Companies

In October 1995, a set of questionnaires was sent by post to a total of 110 UK companies involved in recycling plastics (BPF, 1993; DPA, 1994; BPF, 1996). Figure 7.8 shows the spatial distribution of these companies. Nearly all of these companies are located in the southern half of the UK's mainland, without having any centralised/clustered pattern in their distribution as in the case of Bangladesh. However, it shows that plastics recycling activity in the UK is urban centre oriented.

Out of the number, 41 companies completed the questionnaire and sent them back, representing a 37 % return rate (which is quite good !). Among these 41 companies, 34 were currently carrying out recycling, 6 did not recycle, and 1 company refused to provide any information. Total production capacity of these 34 companies was 6,333,406 tonnes per year of which only 9.5 % was currently used for production. On the basis of the responses received from the 34 companies, the status of the UK plastics recycling companies was assessed and also presented in a series of self explanatory tables as in below.

Table 7.6 shows that 69 % of the total 32 companies responded were established during 1970s, 1980s and 1990s, and 78 % of them started recycling plastics during this period. These companies' feedstocks were collected from all over the UK, with the addition of Ireland and Germany. Most of the feedstocks were industrial scraps (88 %), followed by commercial (53 %) and medical sources (26 %) as shown in Table 7.7. Regarding the nature/type of plastic waste, 75 % respondents were using discarded plastic materials made of virgin polymer, and 35 % were accounted for discarded plastics of recycled polymer (Table 7.8). Some of them used both of these two types of discards in mix and other did separately.

More than half of the respondents' end products was recycled granules, which was followed by recompounded pellets, pellets, finished plastic products, powder and washed flakes (Table 7.9). 26 % of the respondents were doing test for their products quality control, and 33 % believed that quality of feedstock affect the quality of their end

Figure 7.8: Distribution of plastics recycling companies in the UK.

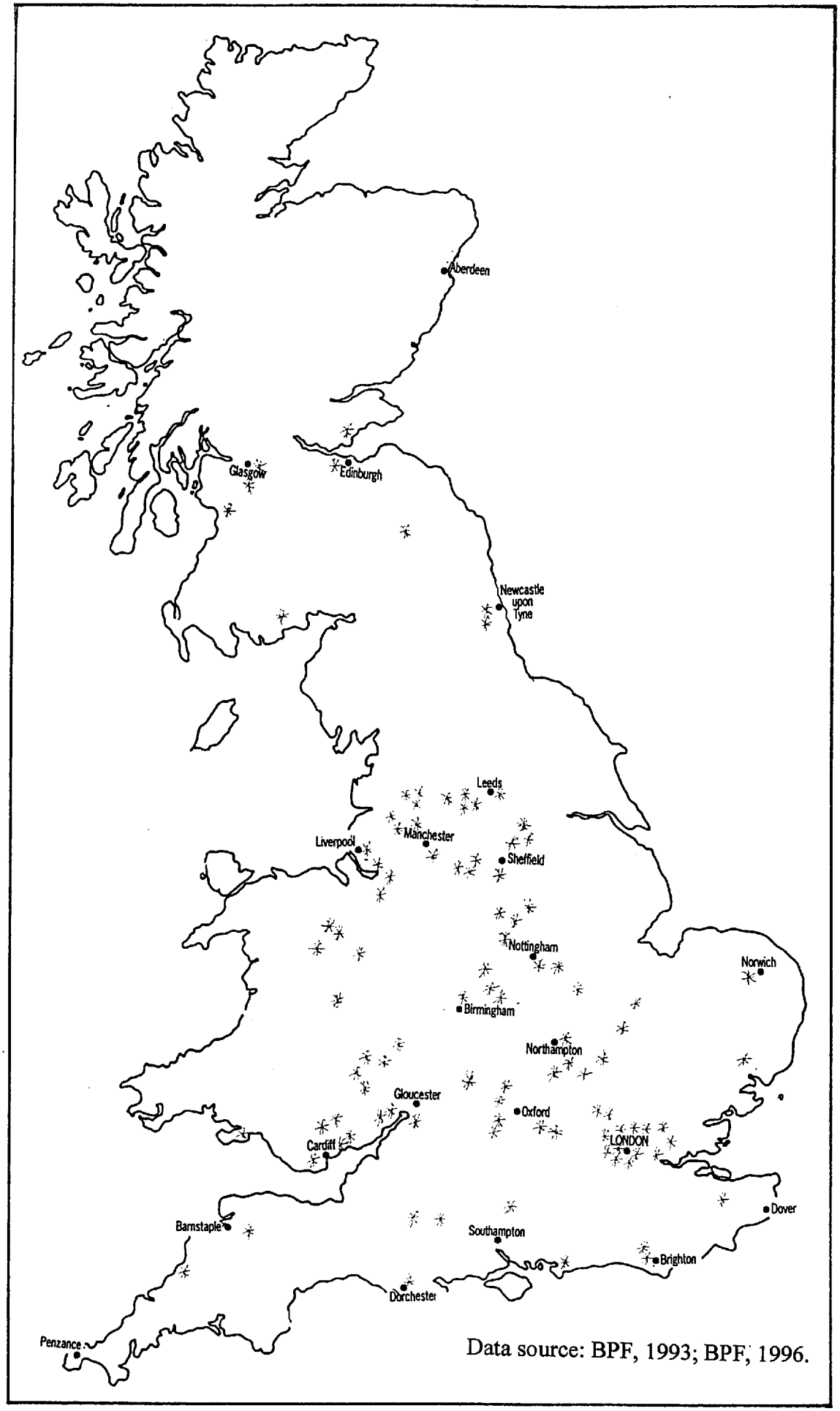


Table 7.6: Year of establishment and of starting reprocessing of the UK plastics recycling companies, 1995.

Year	Before 1950s	1950s	1960s	1970s	1980s	1990s
Number of companies established	2	3	5	9	11	2
Number of companies started recycling	0	1	4	5	15	5

Table 7.7: Percentage of the UK plastics recycling companies by their feedstocks' source of arising.

Sources	Number of respondents (multiple answers)	% of the respondents (Out of the 34 companies)
Industrial	30	88
Commercial	18	53
Medical	9	26
Domestic	7	21
Agricultural	6	18
Transport	5	15
Institutional	2	6

Table 7.8: Nature of feedstocks used by the UK plastics recycling companies.

Feedstocks' description	Number of respondents (multiple answers)	% of the respondents (Out of the 34 companies)
Discarded plastic materials made of virgin polymer	25	75
Discarded plastic materials made of recycled polymer	12	35
Both in mix	10	29
Both but separately	9	26

Table 7.9: The UK plastics recycling companies by their end products' type.

End products	Number of respondents (multiple answers)	% of the respondents (Out of the 34 companies)
Granulate	19	56
Recompounded pellets	15	44
Pellets	10	29
Finished plastic products	8	24
Powder	3	9
Washed flakes	1	3

Table 7.11 lists 15 different properties/parameters which were utilised by the respondents to test their end products. Most common parameters were melt flow index, impact, tensile, colour and level of impurities. About 50 % of the respondents believed that level of impurities (extraneous substances) in feedstocks was one of the major problems in their processing and thus affected the quality of finished products (Table 7.12).

Table 7.10: Quality control initiatives taken by the UK plastics recycling companies.

Description of initiatives	Yes		No		No answer	
	Nos.	%	Nos.	%	Nos.	%
Companies do test for their products' quality control	26	76 %	6	18 %	2	6 %
Companies maintain national/international standard for their products	12	35 %	22	65 %	0	0 %
Companies believe that quality of feedstock affects the quality of end products	33	97 %	1	3 %	0	0 %

Table 7.11: Properties considered in testing end products' quality by the UK plastics recycling companies.

Properties	Number of respondents (multiple answers)	% of the respondents (Out of the 34 companies)
Melt flow index	14	41 %
Impact	12	35 %
Tensile	8	24 %
Colour	8	24 %
Level of impurities	6	18 %
Density	5	15 %
Softness/Hardness	3	9 %
Moisture contents	3	9 %
Finishing	2	6 %
Dimensional	2	6 %
Viscosity	2	6 %
Particle/granule size	2	6 %
Gel content	1	3 %
Ash content	1	3 %
Heat stability	1	3 %

Table 7.12: The UK plastics recycling companies' opinions about the major factors affecting the quality of their end products (by number of respondents; multiple answers).

Factors	Factors associated with reprocessings	Factors associated with feedstocks (in No.)
Impurities	6	15
Mixing of materials/ separation efficiency	6	9
Machine malfunction	3	-
Temperature	3	-
Pre-washing	3	0
Stability/Processing consistency	3	1
Removal of gas	3	-
Operator error	2	-
Cleanliness	2	4
Control of additive modifiers	1	-
Granulate chip	1	0
Melt flow consistent	1	1
Dampness	1	1
Colour	1	1
Uniformity	1	0
Removal of moisture	1	-
Viscosity	0	1
Size reduction	0	3
Availability	-	3

Note: " - " = Not applicable.

7.6 Future Targets and Needs

Out of the major polymers in the UK current market, almost 1.7 M tonnes are in the packaging sector and most of this in the polyethylene and polypropylene markets (O'Neill, 1997). It is estimated by a market analysis that there will be approximately 2 M tonnes of plastic packaging waste by 2001 which need to be recovered by 50% i.e. 1 M tonnes (O'Neill, 1997). One of the reasons for estimating this increase is that a large quantity of imported packed goods finds its way into the UK waste stream and therefore must be recovered.

There is at this moment no guarantee that the future plastics recycling targets of the UK can be achieved (Table 7.13). It is certain that other forms of technology such as

feedstock/chemical recycling are needed in order to meet the overall recovery and recycling targets. The identified market for plastic scrap is dominated by the requirements to collect and recycle almost 160 ktonnes of film. It is therefore clear that the success of the industry to meet the target will be in the plastic film area.

Table 7.13: The future plastics recycling targets of the UK.

	1994	2001
Mechanical (ktonnes)	79 (4.5%)	268 (14%)
Feedstock (ktonnes)	0	35 (2%)
Total (ktonnes)	79	303
% of total market	4.5 %	16 %

Source: O'Neill, 1997.

The new technology of 'feedstock recycling' is still being researched in the UK and is planned to make a significant contribution to recycling industries' performance. In the meantime, Germany has been able to use this technology to meet its targets (O'Neill, 1997).

UK has also a strategy for energy recovery from those plastics packaging materials which are not suitable for mechanical recycling. Currently, the UK is at the bottom among the Western European countries in energy recovery from plastics wastes with a capacity of using only 4% MSW (APME, 1997). It is expected that building a number of new plants would increase its incineration to energy recovery capacity to use 12 % (4.3 M tonnes) by 2000 and up to 20% by 2005 (O'Neill, 1997). After selection of the better quality material for recycling, recovery of energy from packaging waste could account for about 8% of packaging, although achievement will require a greatly increased effort to collect separately combustible fractions (O'Neill, 1997). Since cost of recovering plastic waste is expensive, the UK recycling industries have demanded the right to pass these costs as to the consumer.

In order to meet the future recycling targets, a new collective scheme VALPACK has been established to co-ordinate the plastic packaging industries response to the government (O'Neill, 1997). It is expected that with the co-operation to be extended from this organisation all different plastic recycling sectors will come together to take

the necessary initiatives. Realising the requirement of a body to co-ordinate all the different operations, the materials organisation for plastics -VALUPLAST has been set up to bring together the various recycling activities (O'Neill, 1997). It is envisaged that a substantial progress in plastics packaging waste recovery and recycling will be achieved over the next few years with the instrumental role of this material organisation, and thus requirement of the packaging legislation will be met (Ogilvie, 1996). At the same time, present barriers to plastics recycling e.g. risk of contamination, costs of recovery and market dependency of recycled plastics on the prices of virgin materials need to be minimised by prospective initiatives.

7.7 Needs for Determining Future Scenarios through Modelling

Bearing in mind all the experimental results and the above discussions made so far in this Chapter and also in the previous Chapter 4 and 5, properties of PE are generally degraded during reprocessing, even under known processing conditions. Therefore, it is important to determine the future scenarios of plastics recycling in the UK, considering all uncertainties involved, before dealing with any future recycling targets, adopting and implementing any EC Directive related to plastics recycling. It is crucial to do so earlier rather than later in establishing and emphasising any legislative or market based measures and infrastructures for improving the current poor situation of post-user plastics recycling in the UK.

CHAPTER 8:

Conclusions and Recommendations

8.1 Conclusions

The current problem of study as introduced at the beginning of this thesis posed a number of questions about the operation of plastics recycling in both the developing and developed economy. The central thrust of these questions was to determine the ultimate limit to successive recyclings of plastic waste, more specifically, in a closed-loop system.

The subsequent chapters have identified the inherent characteristics of the systems in the case study countries (Bangladesh, India and the UK) through literature research and fieldwork in Dhaka, Calcutta and Delhi. These chapters have also determined the effects of successive processings on the properties of virgin and general scrap HDPE (High Density Polyethylene), which have been used to try and answer these questions. Determination of both the effects of in-house reprocessing and recycling under real conditions on some of their mechanical and rheological properties have been performed, following standard experimental procedures. On the basis of the results obtained so far, some mathematical models have also been developed to determine future scenarios of plastics recycling and landfilling for Bangladesh, only, due to resource and time limitations.

This chapter presents some conclusions and recommendations based on the research and identifies a number of areas which could benefit from further work.

Overall, limits to plastics recycling in a country are inversely related to its level of economic development. Cities in the developed countries are found to generate large amounts of plastic waste but with much less amount of that waste going back to any resource recovery-recycling system, as opposed to their counterparts in the developing countries. For example, the UK with its 58 million population produced 2,193 ktonnes of post-user plastic waste in 1995 of which 4.6% and 4% had been mechanically recycled and energy recovered, respectively (Table 8.1). On the other hand, in 1994, Bangladesh generated only 12.4 ktonnes of the waste and almost all of that amount (around 98%) had been mechanically recycled and marketed.

Table 8.1: Key statistics of the post-user plastic waste in Bangladesh, India and the UK.

Variables \ Country		Bangladesh[1] 1994	India[2] 1994	UK[3] 1995
Population size (In million)		111	888	58
Waste generated (ktonnes / Year)		12.4	323 (1987-88)	2,193
Waste management by:	Mechanical recycling	98 %	80 %	5 %
	Feedstock recycling	0 %	0 %	0 %
	Energy recovery	0 %	0 %	4 %
	Incineration without energy recovery	2-3 %	20 %	91%
	Landfill	(mainly landfill)	(mainly landfill)	(mainly landfill)

Data Source: 1/ Haque, 1994; BBS, 1996; 2/ Ratra, 1994; Bhandare and Mukhopadyay, 1996; 3/ APME, 1997.

However, the central conclusion arising from this research is that increasing number of successive processings of both virgin and scrap HDPE either under known/controlled or unknown processing conditions are shown to affect substantially their mechanical properties rather than rheological properties.

Some of the experimental results are in general accordance with assumptions made at earlier stages of the research but some are not. A total of 9 different representative batches of HDPE (1 batch of virgin pellets and 8 batches of general scraps) were collected from Dhaka waste streams, and their properties measured (in London) against their number of times processed previously under existing recycling systems (in which the wastes are processed under unknown conditions using manually operated machines). The results obtained from mechanical and rheological tests show that an insignificant change has occurred in their toughness performance, along with a small increase in the MFR, considerable decrease in the stress at break, and catastrophic fall in both the stress at yield and the strain at break (becoming brittle). Similar results have been obtained for the sample HDPE batches collected from Calcutta and Delhi (3 different batches each) waste streams. Different batches from these 9 batches collected from Dhaka were also reprocessed for different numbers of times, with a maximum of seven times for the virgin pellets, using a single screw extrusion-blow-moulding machine (under uncontrolled processing conditions) in Dhaka. Subsequently their tensile strengths and MFR values were determined in London. No attempt was designed to test their other properties due to the limitations involved.

Contradictory results have been obtained for the same batch of virgin HDPE collected from Dhaka plastic market and successively extruded up to fifteen times under known processing conditions in London. Insignificant changes occurred in viscosity measurements. A steady decrease in the MFR after six processings and an overall decrease in the impact fracture resistance was observed which opposes the results determined for other properties: the fall in stress at break, strain at break, crack propagation resistance, and toughness assessment factor. In brief, the virgin material behaves differently after four to six times of in-house successive extrusions even under known processing conditions, and becomes increasingly dull in colour, more brittle and less impact resistant. This set of results was compared with the results obtained from successive in-house extrusion-blow-mouldings on the same batch of virgin pellets, and the former case (in-house successive extrusions) shows relatively higher values for stress at yield and strain at break and lower values for stress at break than those values for the latter case.

All these facts indicate that there is a limit to mechanical recycling of plastic waste from both the perspective of developing and developed economies. The experimental results have shown that HDPE plastics can be processed repeatedly up to four to five times without having significant degradation (any change either increasing or decreasing) in the properties of recycled products. After these processing numbers it would be difficult and uncertain to achieve the expected quality of the products. However, this limit could be pushed further, depending on the availability of necessary recycling ideas, techniques and technology, markets for recycled products, socio-economic and legislative incentives, and environmental awareness.

For instance, plastic waste recycling with its inherent difficulties and multi-staged activities in Dhaka, Calcutta and Delhi has a great role in reducing municipal waste disposal problems, conserving scarce resources, and saving foreign exchange required for importation of virgin plastics. It also creates employment opportunities for the poor children, men and women of different ages who are self employed in this strenuous job of scavenging the wastes. Despite all the different difficulties facing by the recyclers in these metropolises, nearly all plastics fractions in the solid waste streams are accumulated and recycled, because their recycling systems are always favoured by a number of socio-economic and environmental conditions. These wastes are also brought

into these metropolises from other cities and rural areas. At the same time, the recycled plastic products are marketed throughout the countries and beyond. Thus thousands of workers of different age and gender are involved in these activities and maintain the whole system of recycling in an efficient way.

The closed-loop plastics recycling system in Bangladesh is attributed and operated with more than five to six recycling loops. In this country, the waste materials processed 13 - 14 times over the course of these five to six successive recycling cycles, and the recyclers are producing marketable products even using very dull black plastic materials already processed previously about 13/14 times under the real conditions of existing recycling system. This is due to the fact that in many applications (e.g. domestic and light commercial uses) tough mechanical performance is not very important, and the mechanical performance of these black materials recorded in this study is just adequate to serve their purpose.

Such a detailed investigation could not be done for India and the UK due to the time and resource constraints under the limited scope of the current study. Nevertheless, it is quite reasonable to believe, based on the information obtained from literature and fieldwork in Calcutta and Delhi, that the Indian plastics recyclers also producing marketable consumer products using very degraded materials. In general, plastics recycling system in the Indian metropolises is very similar to the system operating in Bangladesh. This system is old and time-tested in both the countries. The forces that drive recycling of plastics in Dhaka city are the same as those in Calcutta, Delhi and probably in other cities of developing countries. The plastic waste recycling systems in these metropolises are operating in an informal, but nevertheless very well organised sector. A large number of people are inter-connected and inter-dependant on plastic waste trading and recycling. However, the Indian system is vast and more specialised in comparison to the system operating in Bangladesh. The former system is one step forward technologically and conceptually in terms of recycling efficiency and moulding them into higher grade applications. The Indian system is also well equipped and exceptionally supported by its large hinterland of recovered materials and a huge market for recycled products. In most cases, it involves large industrial establishments compared to the relatively small units in Dhaka. Moreover, contrary to the locational pattern of plastic recycling units in Dhaka city where most of the units are concentrated in a small area of the old part of the city,

recycling units in Calcutta and Delhi are developed into a clustered pattern located in various places depending on local factors such as location of slums and/or low class residential areas, closeness to landfill sites, availability of land suitable for waste transport, recycling and trading. In addition, India has strong international linkages compared to Bangladesh for the importation of plastic waste for recycling along with their huge amount of national waste arisings.

Besides the common technical problems connected with recycling polymers, there are paramount differences between the functional limitation/extent of plastics recycling in developing and developed economies in terms of their recycling opportunities, driving forces, and availability of technology. The presence of stringent legislation and environmental and hygienic awareness, and the lack of the market for recycled plastic products, results in plastic waste recycling in the UK following a very narrow and restrictive approach as evidenced by the literature search and questionnaire survey on more than one hundred British plastic reprocessers. The plastics industry in this country, and also in other developed countries, has paid attention to the issue of recycling for many years, but this has mainly been focused on the reprocessing of plastic materials discarded from production processes. It has also been recycling homogeneous post-user plastics which are easy to collect and process. More recently, these industries accepted the challenge of recycling of heterogeneous scrap plastics collected from the genuine post-user waste streams based on new technologies of separation, washing, shredding and processing.

All these above mentioned facts imply that the hypotheses postulated at the beginning of the current study are confirmed with some exceptions. Over the course of successive recyclings, properties of plastic waste are degraded seriously and become worthless in the perspectives of developed economy only, rather than the developing economy. Despite these facts, there are serious uncertainties associated with plastics recycling in developing countries as is demonstrated by the results obtained from mathematical modelling of its future scenarios. A woeful situation may appear in Bangladesh and India in the foreseeable future, if certain legislative measures are introduced to maintain quality of recycled products through prohibiting recycling beyond five to six process numbers, which will ultimately result in landfilling a considerably large amount of reclaimed plastics restricted for further applications.

Moreover, the consumption of plastics is growing rapidly world-wide, particularly in developing countries. Waste plastic causes environmental problems when deposited on land and in water; its landfill or incineration causes chemical pollution from large-scale plastics fires; yet separating mixed plastics, and often contaminated plastics for recycling, is expensive (Meharg, 1994; EEP and IES, 1997). More importantly, plastics recycling generates substantial socio-economic and environmental benefits in developing countries. Reclamation of the waste is often labour intensive and unhygienic. It offers significant employment opportunities as well as reducing demand for scarce virgin materials. Recycling can also relieve waste collection authorities of some of the burden of waste collection, since much of the material is separated at source.

In addition, plastics recyclers in Bangladesh and India often mix a portion of higher grade materials with their lower grade feedstock to improve and maintain the quality of recycled products at a desired level. Nonetheless, strong incompatibility among different types of plastic from mixed waste stream gives rise to recycled materials of heterogeneous nature which would be very difficult to process in the next recycling cycle and/or have inferior mechanical properties in recycled products.

There is no appreciable formal waste collection system in Dhaka, Calcutta or Delhi. Open, rectangular, concrete dustbins on the road side are used to dispose all types of post-user wastes together. As a result, post-user plastic waste becomes dirty, mixed with various polymer types, intermingled with non-plastic waste, and sometimes, cross contaminated by infectious wastes. These wastes are unhygienic to collect, labour intensive to sort and clean, and limited to some specific low grade applications.

The quality of the recyclates can be further worsened due to the effects successive recyclings on their properties resulting from the formation of lower molecular weight fractions, low-viscous fractions, possible presence of some degree of crosslinking, and oxygenated groups (Mantia and Curto, 1993; Ram and Getz, 1984; Winter, 1993). In some of the literature, it has been indicated that these forms of degradation can occur during successive processing through roll milling, extrusion and/or moulding, and during use as products (Mantia and Curto, 1993; Ram and Getz, 1984). Williams and Bevis (1982) showed that addition of pigments, ultra-violate stabiliser and recycled

material can cause marked changes in microstructure and impact properties of a polymer.

Therefore, it is also reasonable to accept that a deleterious level in the quality of recycled products may come at an earlier point and have much greater economic significance for plastic recycling systems in developing countries compared to the recycling systems in the developed countries. The reason is that the former deals with a much higher percentage of contaminated plastic waste being recycled and its overall socio-economic importance in the production of recycled plastic products is substantially greater.

8.2 Recommendations

In developing countries, collection of scrap plastics employs the largest number of children, men and women of different ages in the recycling process. They are self employed in the strenuous and hazardous job of scavenging the wastes with bare hands and feet, mainly from the municipal dustbins and landfill sites, and collecting the recyclables which are subsequently sold to the waste merchants. Subsequently, the materials are segregated into eight major resin types and fifteen to twenty five colour categories. This stage of sorting is also identified as the second crucial stage in the recycling process. Therefore, in the first instance, greater attention should be paid to these group of people involved in direct contact with waste plastics by providing waste education, social education, free medical treatments, and tap water facilities at the landfill sites and other major waste collection and waste business points for washing/cleaning themselves after their work.

A higher number of intermediate stages between waste sources and moulding factories and the complex nature of the waste stream are two of the most important problems for plastic waste recycling in Bangladesh and India. The former reduces marginal profit at the end of each stage of waste stream, thus raising the total cost of recycling. The latter facilitates the process of cross contamination, leading to quality deterioration in the recycled plastics. In addition, the lack of sufficient water supply at a subsidised rate for cleaning and washing plastics, and a regular power supply to run shredding, pelletising,

and moulding machines for twenty four hours will undoubtedly remain a major obstacle to the recyclers in Dhaka, Calcutta and Delhi. All these problems have to be eliminated under the care of the responsible authority, in order for the businesses to be maintained in a profitable state and thus the quality deterioration in the recycled plastic products may be minimised.

It is obvious that the easier the plastic is to clean, the more economical it will be to recycle. Once it is in the municipal solid waste stream and thus becomes dirty, the processing cost of reclaimed plastics can be high. An alternative approach is to collect the plastics before entering the dustbin. This could explain why most successful recycling schemes in the developed world to date entail separation before collection. If a householder has to separate different polymers, an improved means of identifying resin types should be established. This can be achieved by printing different colour codes for different polymer types on the products. It is essential that consumer co-operation is obtained to achieve source separation of waste materials to increase their quality and economic values, and raise standards of hygiene. However, although, it seems this recommendation is not practicable on short term basis for Bangladesh or India, some necessary efforts (waste education through mass communication media) should be made on a regular basis at the public level with a long term objective to improve the situation gradually and finally reach to the above goal.

Increased reclamation of plastic waste can also reduce cross contamination problems and improve the urban quality of the city. Again this can be achieved through source separation and extension of life of plastic products, especially polythene shopping bags. In view of the multifarious usage of polythene bags and the harm these do, they are not easy to eliminate, but with care, it may be possible to minimise damage to a large extent and this can be done by storing torn or used polythene goods, which are apparently useless. Later on, these may sold or delivered to hawkers and waste pickers for use again in polythene bags making or any other application. Thus, a necessary evil may become a source of some income to house-wives and young children as well as increasing the supply of recyclable polythene waste. Citizens of these countries will not become motivated to solve the environmental, technical and economic problems in disposing and recycling plastic waste, because they are still not faced with a rising cost of waste disposal, as is occurring in many developed nations, and there is poor legislative control

over urban waste management. An awareness in this respect may be aroused among the population through radio, television, press and other media in order to minimise the effects on the general environment.

An integrated plastics recycling system would feature a sorting facility, processing facility, compounding facility and product forming facility, thus increasing margins between raw material cost and selling prices. This can be achieved through organising and unifying existing small recycling units into a co-operative society. In this respect, all sorters, cleaners, washers, shredders and moulders would be required to become members of a registered co-operative society, which would involve sharing of both profits and losses among the members. The executive committee of the society would formulate a common policy to protect the interests of the society and workers involved, to exert pressure on the suppliers of reclaimed plastic waste and buyers of recycled products, and to accumulate capital for further investment. The society would also be expected to comply with all relevant environmental legislation and regulation.

Geographical location of recycling units within the setting of any urban centre from where most of the plastic wastes originate and their accessibility and connection with the country's transport network, in particular, river transport system could be important factors/contributors: (a) in minimising cost of transporting recyclables to accumulate them at certain suitable places for recycling from different parts of the country, and also, (b) in reducing the pollution resulting from land transportation of the waste. Therefore, any future planning for improving plastics recycling efficiency must consider these geographical factors.

In order to achieve environmental improvement, the understanding of the current situation of plastic waste in Dhaka, Calcutta and Delhi and the desirable actions required for these cities are summarised in Table 8.2.

Experience shows that, even if community bins are provided, these are not used or used only improperly while the refuse accumulates outside the bins. Indiscriminate throwing of garbage on the road must be controlled and the refuse must be containerised at the point of generation. Therefore, any change in waste management or waste disposal technology should be coupled with an initiative to elicit public co-operation and to avoid random

Table 8.2: Existing situation and desirable actions for plastic waste disposal system in Dhaka, Calcutta and Delhi.

Events / Sources of plastic waste	Existing Situation	Desirable Action
Household and commercial plastics	◊ Most attractive plastics articles are recovered at source for reuse at the source; ◊ Most attractive discarded plastic articles/portions are recovered at source to sell to hawkers for recycling or reuse at other than source. ◊ Indiscriminate disposal of those recyclables (which seem not worth recovering and storing at source) in mixture of non-recyclables at outside community dustbins and road sides.	* Better product design to offer more suitability for reuse and recycling. * Identify and advertise the reusables and recyclable plastic articles/portions. * Stopping indiscriminate disposal of less attractive recyclables rather than disposing them separately for ease of collection, sorting, washing and processing. * Separate collection of all recyclables. * Increased recycling efficiency. * More fundamental research to minimise the mechanico-chamical effects on the properties of recycled plastics. * Health care for the pickers and recyclers.
Industrial and institutional plastics	◊ Almost all discarded plastic articles / portions are recovered at source to sell to hawkers for recycling or reuse at other than source.	* Identify hazardous plastic items. * Advertisements and social education not to reuse or recycle hazardous items. * Separate collection and disposal of hazardous items. * Ensure safe disposal of hazardous items. * Health care for the pickers and recyclers of non-hazardous items.
Hospital plastic wastes	◊ All plastics items are infected as these are disposed of with other infected recyclables and non-recyclables. ◊ Some plastic items are recovered at source for reuse.	* Identify infected and hazardous plastic items. * Stop reuse and recycling of such items through social education. * Separate collection and disposal of these items. * Ensure their safe disposal by proper and effective incineration method. * Further research to explore alternative methods for their safe disposal. * Ensuring health and safety at work for the staffs handling hospital wastes.
Final disposal of plastic waste: a) municipal area:	◊ Open dumping of useless plastics, including those plastics which are difficult to recycle. ◊ Separation of recyclables by pickers. ◊ Indiscriminate filling up of water bodies and waterways.	* Modified sanitary landfill. * Health care for the pickers. * Immediate stopping of indiscriminate filling up of water bodies and waterways.
b) Outside municipal area:	◊ No regular dumping of plastics along with other wastes. ◊ Indiscriminate filling up of water bodies and waterways.	* Identifying regular dumping places. * Immediate stopping of indiscriminate filling up of water bodies and waterways.

Note: After the framework utilised by EIP (1996).

dumping of domestic refuse anywhere on the street at any time. In order to reduce cross-contamination of plastics whilst these are generally disposed of in the mixed waste stream, the need for special arrangements for solid waste collection and temporary storage in multi-storied buildings must also be emphasised.

An efficient plastics recycling system involves a great deal of planning and management inputs, because of the following reasons: (a) the system depends on labour-intensive techniques for collection and transfer of recyclables, (b) the system requires public education and encouragement; (c) daily preventive maintenance and ability to meet major repair needs are essential to keep the recycling equipment steadfast in order to reduce the mechanical effects of reprocessing on the properties of plastics.

Last, but not least, is the point of management. In the long run, say, over a 25-year span, as the metropolis grows in area and population, there would be changes in the solid waste composition and the system of solid waste management should be capable of adjusting. Following the view of Giri and De (1992), it is necessary, therefore, to formulate a long term management plan for the solid waste sector, indicating broadly the possible evolution in the solid waste (including plastics) disposal system in terms of the mode of transportation, the modes of disposal and the disposal sites. Since planning is not possible without a reliable information base, a research cell should be setup, which would systematically collect data for the solid waste sector at regular intervals, analyse and evaluate the performance of the system and its equipment, and make recommendations for adjustments.

As the result of a lack of stringent legislative measures and lack of implementation of the existing regulatory measures in the countries of the developing economy, a considerable amount of hazardous plastic wastes (originating from both within the country and imported from abroad) enter into plastic recycling system. In the case of India, for example, the section 11 of the Hazardous Waste (Management and Handling) Rules, 1989 states that *'import of hazardous wastes from any country to India shall* (not) *be permitted for dumping and disposal of such wastes'* (Desai, 1994, p.151-158). The Rules added that *'import of such waste* (including discarded container and container liners of hazardous and toxic channels and wastes) *may be allowed for processing or reuse as raw material, after examining each case in merit by the State Pollution Control Board or by an officer*

authorised in this behalf'. Obviously, the situation is different from that in developed countries. Since, waste related rules and regulations are not generally followed or practised in the developing countries which address aesthetic, hygienic and environmental issues, it needs in-depth study and analysis on some issues such as: how does international waste trading affect the waste disposal and recycling system in the developing countries, and whether this trading of waste helps or disturbs the developing countries' activities in minimising quality deterioration in the recycled products, especially plastic products?

In addition, it is claimed that the difference between packaging wastes recovery targets (50-65%) and recycling targets (25-45%) set in the EC Packaging Directive (O'Neill, 1997), and recent trade liberalisation (EEP and IES, Undated) are likely to encourage flows of recyclable waste from industrialised to developing countries EEP and IES (Undated) reported in their research project that in general supporters of this trend of international waste trading believe that it contributes towards a more efficient global allocation of goods and services, and it also encourages growth and stability in the recycling industries of the south. It is also mentioned in the project that opponents of this issue generally argue that international trade provides an easy route for dumping waste on developing countries (EEP and IES, Undated) rather than recycling the waste as is expected in the Western European countries (APME, 1997). They are also concerned about the environmental impacts of the international transportation and the undermining effects on the local recovery sectors. These views highlight the uncertainties surrounding the effects of waste trade on developing countries. Therefore, these issues for India and Bangladesh need to be examined by emphasising the human and environmental factors as in the case of a research project on China that was due to be completed by February 1998, conducted by a number of international organisations (EEP and IES, Undated).

Moreover, piles of dirty plastic films are also burnt openly to agglomerate them for purpose of recycling in India and Bangladesh. At the same time the recycling system is prone to misuse, particularly through adulteration and unhygienic packaging in the secondary market. Considering these problems along with the increasing and very large population base, the potential large volume of unhygienic plastic waste, and its uncontrolled application arising from reuse and recycling, it is necessary to evolve an integrated eco-friendly product management system in these countries, including India and Bangladesh, as claimed by Parasuraman and Banerji (1994). Following the lack of proper

initiatives, all these problems could become insurmountable, since the waste generation in Dhaka city (also probably in Indian cities) is increasing every year with a linear trend (Sarkar, et al., 1995). Thus, the procedure of collection, transfer and transport, disposal and dumping have to be planned in a scientific way and to be governed by definite regulation, both in the metropolitan and municipal areas to protect the environment.

Apart from the inherent environmental consequences which are directly linked with the operational processes of recycling, plastics recycling in Bangladesh and India are well managed sectors. However, following the view of Ganguli (1995), here it is emphasised that, taking only the unhygienic and environmental issues related to plastics recycling, policy makers and regulators should not strike at the roots of plastics recycling and displace the millions of people connected with the system. The 'human factor' needs special consideration in these developing countries, but at the same time, it would be a self defeating effort if their policy makers neglect those unhygienic and environmental issues inherited by the plastics recycling systems. As a result, the future key management issues identified in this work, same of which concern with the views of Ganguli (1995) are:

* Changing consumption habits in the society.
* Reducing the volume of waste at the source.
* Developing new technology for efficient recycling.
* Investigating feasibility of introducing biodegradable plastic in the case of short-life plastic products.
* Setting appropriate regulatory standards.
* Finding out methods for reduction of health hazards of waste pickers and recyclers.
* Identification of particularly hazardous and toxic consumer products requiring special waste management units.
* Obtaining regulatory and policy support at all stages of the recycling.
* Introducing modern management skills within the near future, focusing on a sustainable recycling system.

Despite the importance of environmental benefits of recycling in the development of plastic waste recycling schemes, the cost of recycling, as in all industries, is another controlling factor. Any recycling process should be able to compete in the open market with a product of comparable quality to the original material, and at a price below the

price of the original material cost. Successful recycling efforts require wide markets for the recycled articles and an overall recycling process that saves energy (compared to the standard manufacturing process) and offers a cost advantage over virgin resins.

There is modern recycling equipment available in developed countries but these are expensive and not viable economically in the context of developing economy. Therefore, plastic recycling in the developing economy requires some innovative ideas and locally available appropriate technologies and equipment which should be able to prevent quality deterioration of the recycled products and also minimise the cost of recycling through energy saving in order to advance the current recycling system towards a sustainable future. It also requires careful planning and changes in attitudes. Much more importance from the socio-economic point of view and special consideration to waste pickers by providing health and economic protection, will have a substantial impetus in minimising the current plastic recycling problems and will also certainly extend the limits of the recycling.

Mechanical recycling of plastics in developed countries is also facing a range of technical, socio-economical, and legislative barriers as discussed in Chapter 7. In order to minimise polymer degradation during repeated processings, Winter (1993) mentioned that a large number of processing parameters have to be kept under permanent control. Such parameters are temperature, environmental atmosphere, holding time in a melt state, amount of impurities, type of catalysts used and stabilisers, consistency in processings, background history of reclaimed materials, etc.

Therefore, with the aim of reducing the burden on mechanical recycling and inherent difficulties associated with this method, further basic researches need to be carried out into developing economically and environmentally sustainable methods. It is in general agreement with the views of Winter (1993) that 'glycolysis' can be considered as a method for direct re-use, whereas 'methanolysis' and 'hydrolysis' are mainly taken into consideration for monomer recovery. He also noted that although all these three methods are completely realistic, their usefulness under practical production conditions remains controversial. However, in this respect Winter (1993) has discussed critically the limitations of such methods for PET recycling as below:

> "Glycolytic recycling of PET, which can be done in a continuous or in batch process, is preferentially performed by addition of a PET waste to a boiling ethylene glycol (EG), which leads to the formation of low-molecular weight intermediates and eventually to crystallizable diglycol terephthalate (DGT). The rate of the degradation reactions is primarily controlled by varying the holding time and temperature, which depends on a choice of suitable catalysts (e.g. titanium derivatives), and by adjusting the PET/glycol ratio. It is also necessary to avoid side reactions which might occur, e.g., by adding 'buffers' or by keeping down reaction time and temperature. ..... The low-molecular weight depolymerizates can be introduced directly into a polymerisation system, preferentially after filtration. In this method particular care has to be taken in order to avoid glycol ether formation, which may lead to PET of inferior properties. ..... Although this for producing unsaturated resin (for use in regular castings or in fibre-reinforced laminates) has been thoroughly studied by PET-film manufacturers, it is believed that the method is not currently used in production" (Winter, 1993).

Therefore, more efforts must go towards improving versatility of these existing feedstocks/chemical recycling methods.

In the case of reclaimed plastic wastes containing large amount of impurities and other combustible solids, it is important to keep them away from landfills and use them incineration to energy recovery termed 'quaternary recycling'. Strong emphasis is required to be given to optimisation of incinerators in maintaining higher operating temperatures and reducing air pollution. Another alternative for dealing with heavily contaminated plastic waste is the idea of making photo- or biodegradable polymers. Although such an idea has long been in existence, very few pragmatic attempts have been made along these lines. Scott (1976) articulated that the process of combustion is an important means of returning the carbon and hydrogen of which plastics are made to the biological cycle where they are recycled to high energy chemicals (carbohydrate) by means of the photosynthetic process. He also added that research can also be carried out to develop a plastic which can be recycled into the biological cycle by inducing controlled photodegradability followed by biodegradation using the 'delayed action' photo-activator. Nevertheless, there may be some dangers in biodegradation if impurities are present in biodegradable plastics. These aspects need to be addressed simultaneously with the process of developing any biodegradable plastics. In addition, Winter (1993) has explained the current situation as below:

> "Special photodegradable polymers were synthesized for the purpose of having them destroyed after use (e.g. in a landfill). Another approach was the incorporation of the suitable groups (e.g., carbonyl) in the polymer backbone in order to make polymer

photodegradable by sunlight or ultra-violate light. A problem arises due to the fact that light exposure conditions on a landfill cannot be regulated. The main difficulty, however, seems to be practically insurmountable: it is hardly possible to combine rapid degradation upon exposure to light in a landfill after use with a good light-stability of the film during service. ..... Another problem is a combination of desired properties with favourable economics. ..... The main difference between biodegradation and photodegradation lies in the possibility to create in a landfill an environment completely different from that encountered under normal storage conditions; e.g., microorganisms which can be destroy plastic films may be added to a landfill. In spite of the fact that substantial research time was spent on studies in this field, it is claimed that surprisingly little is understood about the molecular-level interaction between polymers and microorganisms. ..... Another approach consists of mixing small amounts of biodegradable polymers, e.g., polysaccharides, with a regular polymer (e.g., a polyolefin), in order to make the end-product distortable as well. ..... Mixture of starch with other polymers ..... have been studied. ..... the starch additives is only needed in small amounts, which hardly alters the properties of an original polymer, might show some promise for future applications. ...There also remain some controversies about the completeness of the degradation of polymer/ starch mixtures" (Winter, 1993).

However, innovative researches for developing biodegradable polymer are still in progress. Its enormous market potential desperately requires a real breakthrough in order to be attained. There is a great potential in the development of a versatile 'new polyester amide', which is currently under trial at Bayer (Germany). This is 100% biodegradable, recyclable and also strong with a high tensile strength and is produced without solvent, chlorine or aromatic ingredients (Bayer, 1998). Depending on the soil condition, its biodegradability varies and it is degradable in composting plants, compost heaps or in soil. In normal use, however, it is not sensitive to water and the material can be recycled in traditional fashion. Its compostability is not even impaired by multiple recycling as this aspect has been fully tested under German standards. Bayer suggest that their plastic is particularly suitable for applications where plastic comes into contact with organic waste (e.g. horticulture, agriculture or the food industry) which can accelerate the process of biodegradability. Again, the contamination problem which is inevitably associated with successive recyclings may affect both the processes of biodegradation and recycling of the wastes.

In this situation, for the time being, it is reasonable to accept the view expressed by Gattiglia, et al. (1993). They believed that, since landfill and incineration are facing increasing opposition due to their rising costs and environmental pollution problems, materials recycling of plastics seems the logical solution for the developed countries to close their plastic loop, unless and until innovation of alternative solutions. In this case, feedstocks recycling deserves more importance and applicability in mixed plastic wastes recycling than their mechanical recycling.

In the meantime, many researchers have produced some creative ideas for mitigating the problem of mechanical recycling mixed plastics. For example, Mantia, et al. (1993) said that a possible route to recycle mixed plastic waste to obtain secondary materials with acceptable mechanical properties could be to blend them with virgin polymers or, at least, with recycled homopolymers. Their experimental results obtained for the blends of virgin LDPE and mixed plastic waste (MPW) indicated that all the mechanical properties, with the exception of elongation at break, are very similar to those of the virgin material if the MPW content does not exceed 50%. The results obtained from another study carried out by Mantia and Curto (1993) revealed that use of the recycled polyethylene (PE) in blending with nylone (Ny) giving rise to PE/Ny graft copolymers during processing, improved the mechanical properties of the resultant material. Castellanos et al. (1993) claimed that the situation will be much more complex if plastics waste consisting of polymer blend. Nonrecyclable polymer blend discards is sent to landfills. As a result, there is a need for a real and practical possibility of recycling of thermoplastic wastes using an integrated management scheme in which plastic wastes are subject to sequential recycling from initial high performance and high cost applications to subsequently lower performance and lower cost applications (Castellanos, et al., 1993). In this respect, it is necessary to create new laws related to generation, collection, and location of sites having economic aspects in mind. In future, additives could be found to improve performance, processing, mechanical properties, surface properties, etc. For instance, alongside the infrared systems of plastic bottle sorting, now a new process is available in France, which is based on one of the principles of artificial intelligence - neural networks (EBM, 1997). This computer based sorting system recognises plastic bottles with similar characteristics and gives a guaranteed purity of 98%. Following the successes in research and development,

mechanical recycling may become the most economical way to manage scrap plastics and turn them into resources.

Finally, since feedstocks recycling involves huge capital costs, a balance must be maintained by the developed countries in their plastic waste management. Mechanical recycling should be encouraged for single grade, clean and easy sorting plastics, and more versatile feedstocks recycling should be directed and developed for the mixed contaminated plastics waste.

8.3 Areas for Further Research

There are a number of areas in which further extension of the research in this thesis would be of benefit. As noted before, the characteristics and situations around plastics recycling could not have been thoroughly investigated for each of the case study countries, due to the limited scope of this thesis. The literature research and laboratory experiments performed in the present study have covered part of the problems highlighted at the beginning, and also have identified the major issues deserving further work. In particular, impacts of plastics recycling on the environment and health of the recyclers need to be addressed in both parts of the world. Such a study with a holistic approach is essential, especially for industrialised countries before any further programmes are embarked upon to achieve the challenging waste recycling targets set by the national and international legislation and directives.

A further area for research might be to determine the ash contents (to measure the level of extraneous particles), and the molecular characteristics of the general scrap plastics against their number of processings performed previously under the real conditions. These tests can also be carried out for the sample specimens collected from their in-house successive reprocessings. Effects of the difference in the procedures of in-house successive reprocessings on the properties of the virgin pellets would also be useful to investigate to a further extent. The aim of such attempts would be to obtain in-depth understanding of the dynamics of their property degradation, resulting exclusively from the reprocessings.

A detailed account of the limitations of the mathematical modelling accomplished in this study has already been discussed at the end of Chapter 6. In this exercise, the major limitation is that plastic recovery and landfill scenario models have been developed on the basis of some assumptions relating mainly to linear growth of virgin plastics import into, and stepped patterns of plastic waste recovery and landfilling in, Bangladesh. Factors related to the recyclability of the waste, the profitability of the recycling operation, and the marketability of the recycled products have not been incorporated in the modelling parameters. Moreover, no sensitivity analysis has been carried out to evaluate the degree of uncertainty involved with the modelling parameters. However, hypothetical legislative factors associated with the quality of recycled products have been considered in the modelling of the future scenarios. All these drawbacks of the modelling clearly demonstrate the need for further work through incorporating dynamic aspects of plastics recycling and landfilling systems as operating in the country. These aspects are the existing continuous waste discarding, recovery and landfill patterns; non-linear trends of import (if it is considered from the actual year of first imports into Bangladesh) and export of the materials; and different waste plastic blending ratios used by the recyclers in the country.

In addition, the hypotheses in this study could not be tested fully, which would require consideration of more parameters involved in plastics recycling to obtain a clear and concrete view of scenarios of the system in both the developing and developed economy.

However, it is obvious that the results and achievements attained from this research show many important and potential applications in developing an effective plastic waste management and recycling strategy in both the developing and developed countries. Moreover, the expertise gathered from the mathematical modelling have potential application and use in further research related to the processes where the aspect of exponential expansion and repeated occurrence of the same events/phenomena after a equal time steps are involved (e.g. demographic, chemical and bio-chemical processes).

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APPENDICES

APPENDIX 1.1: Applications of recovered plastic waste in Bangladesh, 1994.

Plastics Type	Typical Original Use	Recycled Products
Low Density Polyethylene (LDPE)	Film for wrapping, carrier bags, horticultural sheet, packaging of dairy products, toys, and cable insulation.	Re-use: LDPE packets are re-used as plant pots; Recycled: toys, seed bed cover, shading for seedlings and young plants, roofing huts, sheds and boats, and protection against rains.
High Density Polyethylene (HDPE)	Shopping bags, bottle caps, cosmetic casing, bottles for pharmaceuticals, buckets, jerry-cans for vegetable oil, and other domestic articles.	Shopping bags, jerry-cans, toys, household articles, and office accessories.
Polypropylene (PP)	Film wrappings for garments, biscuits, crisps and sweets, disposable syringes, ball point pens (one time use), string and netting, auto bumpers and batteries, and road mats.	Ball point pens, PP sheets, motor belts, packaging belts, and strings for furniture.
Polyvinyl Chloride (PVC)	Bottles for mineral water, body care products, shampoo and household cleaners, pipes, sanitary fittings, shoes, slippers, soles, containers, saline bags and sets, catheters, cable insulation and office folders.	Pipes, sanitary fittings, shoe, slipper and sole, containers, jerry-cans, cable insulation, toys, and tricycle wheels.
Polystyrene (PS)	Ice-cream cups, fizzy drinks glasses, tooth brush, cleaning brush, ball point pen, bottle caps, cosmetic packaging, jewellery and its casing, and cutlery and trays.	Coat hangers, office accessories, and toys, ball point pen, bottle caps, cosmetic packaging, jewellery and its casing, and trays.
Polyethylene-terepthalate (PET)	Fizzy drinks bottles.	Re-use: Re-using for drinking water.
Mixed plastics	Shopping bags, one or two times recycled plastic products, and unidentified resins.	Products with poor mechanical properties: containers for different preparations of tobacco, corks, and lids.

Source: Haque, 1994, and Haque and Bell, 1998.

APPENDIX 1.2: Plastic profile - Indian scenario, 1993 - 94 [Units: x 1000 tonnes].

Polymer	Basic Raw Material	Demand	Production	Uses
PVC	Ethylene (0.48)	402	376	Pipes, fittings, wires, cables, footwear, calendered sheets.
LDPE/LLDPE	Ethylene (01.03)	253	215	Packs, wires, cables, blow and extrusion moulding.
HDPE	Ethylene (0.04)	270	175	Woven sacks, packaging firms, pipes, Injection and blow moulding.
PP	Propylene (1.020)	225	90	Films, fibres, goods, woven sacks, filament, moulding tyres and tubes etc.
PS	Ethylene (0.33)	64	46	Moulded items for electronics, automobiles.
Total plastics		**1214**	**902**	
Synthetic rubber	Styrene, butadiene SBR, NITRITE	130	117	Household appliances, packaging sector, electrical fittings.
Grand total =		**1344**	**1019**	

Note: The difference in the national demand and production of virgin plastics is met by importations.

Data Source: Ray, 1997.

APPENDIX 1.3: Growth of plastic and polymer products in India (Units: x1000 tonnes).

Year	Plastics	Synthetic rubber	Synthetic fibre
1989-90	334.0	52.6	388.8
1990-91	374.9	55.4	436.3
1991-92	438.2	56.0	458.5
1992-93	774.0	56.0	520.6
1994-95	984.0	56.0	706.6
1999-2000 (Expected growth	2147.0	195.0	819.6

Data source: Ray, 1997.

APPENDIX 1.4: Questionnaire mailed to the UK plastic waste reprocessing companies, in 1995.

Questionnaire to The UK Plastic Waste Reprocessors

Return rate: 37 % (41/110).

Note: Please write down or tick as appropriate, and answer as many questions as possible.

ABOUT GENERAL ASPECTS:

1. Do you reprocess plastic waste ?
   (Note: For the purpose of this PhD project ***reprocessing*** *involves shredding, washing, drying, separation, granulating, pellet formation, recompounding and pulverisation.)*
   * Yes [ ]
   * No [ ]---> Go to question no. 20

2. In which year was your company:
   * established ? .....
   * started reprocessing ? .....

3. What is the reprocessing capacity of your plant ?
   * Capacity when started reprocessing .....tonnes/year
   * Current capacity .....tonnes/year
   * Current production .....tonnes/year

ABOUT FEEDSTOCK REPROCESSED:

4. (a) What do you reprocess ?
   * Single grade plastic waste [ ]
   * Multiple grades plastic waste [ ]
   * Commingled plastic waste [ ]

   (b) If single or multiple grade(s), please specify grade(s) or plastic types
   .....
   .....
   .....

5. What material composes your feedstock (processed plastic waste) for reprocessing ?
   * Discarded plastic materials made of virgin polymer.....[ ]
   * Discarded plastic materials made of recycled polymer.....[ ]
   * Both but separately.....[ ]
   * Both in mix.....[ ]

6. What is the distance that feedstock comes from to your plant?
   * Maximum distance.....mile
   * Average distance.....mile
   * Minimum distance.....mile

7. What is the source of arising ?
   * Domestic [ ]
   * Industrial [ ]
   * Commercial [ ]
   * Agricultural [ ]
   * Institutional [ ]
   * Transport [ ]
   * Medical [ ]

8. How much plastic waste from domestic sources did you reprocess in the year 1994 ? .....tonnes/year

*(Note: **Domestic sources** include household, civic amenity site, street sweeping and litter.)*

ABOUT END PRODUCTS & THEIR QUALITY CONTROL:

9. What are your end products ?
   * Granulate -- -- -- -- -- -- -- -- [ ]
   * Washed flake -- -- -- -- -- [ ]
   * Pellets -- -- -- -- -- -- -- -- -- [ ]
   * Recompounded pellets -- [ ]
   * Powder -- -- -- -- -- -- -- -- -- [ ]
   * Finished plastic products --[ ]

10. Do you do any tests for your products' quality control ?
    * Yes [ ]
    * No [ ]---> Go to question no. 15

11. Which properties of your end product do you usually consider in testing its quality ?
    .....
    .....
    .....
    .....
    .....

12. What is the name of the test for each property test of your end product ?
    .....
    .....
    .....
    .....
    .....

13. Do the findings of the test give any indication that the quality of feedstock affects the quality of end product ?
    * Yes [ ]
    * No [ ]

14. What are the main factors you are concerned may affect the quality of your products ?

    a) Factors associated with reprocessing itself:
    .....
    .....

    b) Factors associated with the feedstock:
    .....
    .....

15. What specifications are demanded for your end product by your customers ?

    .....
    .....
    .....

16. Do you maintain any national/international standard for your end product ?
    * Yes [ ]
    * No [ ]---> Go to question no. 18

17. What is the identification number or description of the standard ?
    .....
    .....
    .....

ABOUT OTHERS:

18. Would it be possible to get addresses of your customers ?
    * Yes [ ]
    * No [ ]---> Go to question no. 20

19. Could you please attach a copy of the list of addresses with this completed questionnaire ?
    * List attached [ ]
    * List to be sent later [ ]

20. (OPTIONAL): Name of person completing questionnaire: .....
    Position:..... Company:.....
    Date: .....

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APPENDIX 2.1: Exports of plastics products from Bangladesh, 1992-94.

Description of the materials exported from Bangladesh	Exported to	1992-93 (In US$)	1993-94 (In US$)
1/ Propylene copolymers in primary forms	Poland	0	55,952
2/ Fluoro-polymers other	UAE	11,952	0
3/ Polythene	Singapore	18,048	0
4/ Polymers of vinyl chloride or of their halogenated olefins in primary forms, other	Myanmar	25,494	0
	Hongkong	478,313	0
	Jordan	21,181	0
	Saudi Arabia	0	20,747
	Ukraine	0	40,337
	Russia	43,157	172,699
	Vietnam	164,193	0
5/ Polyethylene derivatives, other	Saudi Arabia	23,422	0
6/ Plastic materials	Singapore	105,976	0
7/ Floor coverings, wall or ceiling covering of plastics of polymers of vinyl chloride	Myanmar	0	73,084
	Honduras	0	40,554
	USA	0	29,831
	Russia	0	86,867
8/ Floor coverings of plastics whether or not self-adhesive, in rolls or in the form of tiles, wall or ceilings of other plastics	Russia	0	86,193
9/ Sacks and bags (including cones) of polymers of ethylene	Australia	13,301	0
	France	164,699	253,494
	Germany	47,639	104,819
	Netherlands	25,687	3,108
	UK	0	12,169
10/ Sacks and bags (including cones), other plastics	From the Export Processing Zone at Chittagong to abroad	0	31,277
11/ Tableware and kitchenware of plastics	Bhutan	0	4,337
	Saudi Arabia	0	482
12/ Articles of plastic materials	Pakistan	506	0

Data source: BB, 1996. Note: (US$ 1 ≈ Taka 41.5 on April, 1996).

APPENDIX 3.1: Average surface temperatures measured at three different points of the moulding machine after production of every 20th jerry-can during successive in-house reprocessing of twelve different categories of HDPE feedstocks in Dhaka.

Notation of the feedstocks	Notations of the samples reprocessed successively in the factory	Nozzle temperature(^{0} C)	Head temperature (^{0} C)	Barrel temperature (^{0} C)
(1)/1	(1)/2	185.3	206.7	151.8
	(1)/3	178.4	189.5	150.3
	(1)/4	196.7	186.9	162.3
	(1)/5	164.8	171.4	142.9
	(1)/6	191.9	206.5	166.3
	(1)/7	179.6	194.5	165.7
	(1)/8	185.2	181.3	161.2
(2A)/2	(2A)/3	174.2	183.3	161.4
	(2A)/4	162.6	187.4	148.2
	(2A)/5	174.6	172.1	143.7
	(2A)/6	188.0	179.0	151.5
	(2A)/7	171.8	172.2	147.3
	(2A)/8	176.9	167.9	150.4
(2B)/2	(2B)/3	152.0	165.9	141.8
	(2B)/4	163.6	177.0	143.1
	(2B)/5	149.9	178.0	145.0
	(2B)/6	156.9	185.1	144.1
	(2B)/7	154.7	185.4	142.5
	(2B)/8	138.7	183.1	139.5
(3A)/3	(3A)/4	168.7	195.0	147.8
	(3A)/5	190.2	182.3	149.1
	(3A)/6	180.1	183.6	144.4
	(3A)/7	174.3	114.9	136.0
	(3A)/8	158.8	120.2	133.4
(3B)/3	(3B)/4	150.2	194.7	140.8
	(3B)/5	171.2	197.9	145.8
	(3B)/6	148.8	192.7	148.8
	(3B)/7	158.2	177.5	143.3
	(3B)/8	151.7	189.3	136.7
(3C)/3	(3C)/4	167.8	179.5	135.8
	(3C)/5	156.2	141.8	148.4
	(3C)/6	144.5	120.8	122.4
	(3C)/7	157.3	129.4	140.9
	(3C)/8	171.2	135.7	142.4
(4)/4	(4)/5	142.8	179.8	138.2
	(4)/6	165.4	177.6	140.5
	(4)/7	160.9	162.7	140.0
	(4)/8	156.6	175.2	135.1
	(4)/9	145.5	178.2	135.8
(5)/5	(5)/6	182.7	195.8	151.1
	(5)/7	189.2	226.8	153.9
	(5)/8	186.3	145.8	150.1
	(5)/9	178.2	149.4	151.0
(6)/7	(6)/8	167.7	221.6	151.5
	(6)/9	149.0	171.5	138.8
	(6)/10	128.7	157.1	126.7
(7)/9	(7)/10	159.3	160.1	115.6
	(7)/11	139.2	160.3	121.1
(8)/11	(8)/12	132.0	156.3	128.5
(9)/14	(9)/15	130.0	157.5	129.2

APPENDIX 4.1: Tensile strength test results for the virgin HDPE extruded successively using a twin screw extruder in London.

No. of Times Processed	Stress at Yield (MPa)	Young's Modulus (MPa)	Energy at Break (J)	Strain at Yield (mm/mm)	Energy at Yield (J)	Strain at Break (mm/mm)	Stress at Break (MPa)
Pro-0	26.9	583	28.73	0.120	0.33	11.07	24.3
Pro-1	27.6	574	27.28	0.123	0.32	10.59	23.9
Pro-2	26.5	601	27.17	0.117	0.31	10.32	23.0
Pro-3	27.4	581	30.50	0.121	0.30	11.51	25.0
Pro-4	27.0	598	25.10	0.121	0.34	10.13	21.5
Pro-5	27.5	580	15.23	0.118	0.33	6.62	12.7
Pro-6	26.7	589	21.94	0.115	0.34	10.06	11.9
Pro-7	27.0	610	23.58	0.113	0.29	9.80	12.4
Pro-8	27.2	576	22.70	0.119	0.34	7.99	14.0
Pro-9	26.4	593	23.77	0.122	0.33	9.60	13.6
Pro-10	26.5	599	18.82	0.119	0.35	7.41	12.1
Pro-11	27.0	610	20.82	0.114	0.33	8.26	11.0
Pro-12	27.0	598	22.48	0.117	0.33	9.02	11.6
Pro-13	26.2	599	22.38	0.107	0.27	9.34	16.4
Pro-14	27.2	620	18.36	0.118	0.36	7.09	14.1
Pro-15	27.6	618	22.32	0.117	0.33	8.88	15.7

APPENDIX 4.2: Weighted linear regression- reasons and procedure

[O. L. Davies and P. L. Goldsmith, eds. (1972) **Statistical Methods in Research and Production**, Imperial Chemical Industries Ltd., Edinburgh.]

In the least squares method of regression analysis, it is generally assumed that the error variance remains the same for all values of y. However, there are many other cases where this assumption becomes invalid. Therefore, it means that the amount and the reliability of the value of y for each x may differ substantially because of unequal number of repeated measurements or samples. Using different instruments may also raise the variation in measurements of the y values even though it is known that accuracy of the instruments being used varies. Thirdly, there is another possibility that certain physical or chemical law causes the error variance directly dependent on x, for instance, Davies and Goldsmith (1972) reported that *"in radio-activity measurements the variance decreases with time"*. In the current study of viscosity, it is likely that experimental error in shear stress measurements may have decreased with the increase in shear rate.

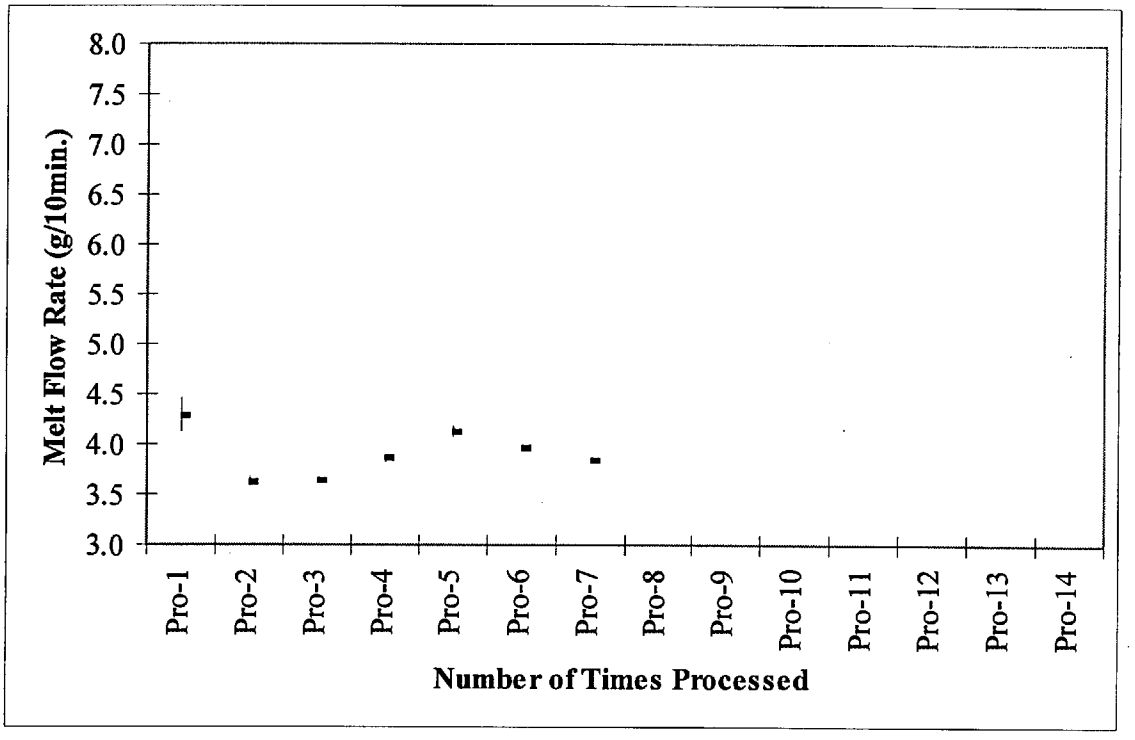
They stated that *"if the variances can be determined, even approximately, it is reasonable to weight each y observation by the inverse of the associated variance, ... $w_i = 1/\sigma_i^2$ "* (Davies and Goldsmith, 1972). In this present study, variances for replicated viscosity measurements could not be determined as because of the shortage of materials as already mentioned earlier. Therefore, the variance, σ_i^2, is replaced with 'error percentages' shown in Table 4.5 (in Chapter 4). Then all of the weight values in fractions, w_i, are multiplied by 10 in order to get the discrete number of data points (NDP) of log of shear stress (ShSt) required to be plotted against their log of shear rates (ShRt) as shown below:

Log of ShRt :	Pro-0/15:	1.29	1.59	1.72	1.90	1.99	2.29	2.47	2.59
Log of ShSt :	Pro-0 :	4.33	4.47	4.54	4.59	4.63	4.73	4.80	4.81
	Pro-15 :	4.39	4.50	4.56	4.60	4.63	4.74	4.80	4.84
Error in % :	Pro-0 :	2.00	1.46	1.24	1.11	1.00	0.80	0.69	0.67
	Pro-15 :	1.74	1.37	1.18	1.08	1.01	0.79	0.69	0.63
NDP :	Pro-0 :	5	7	8	9	10	13	15	15
	Pro-15 :	6	7	8	9	10	13	15	16

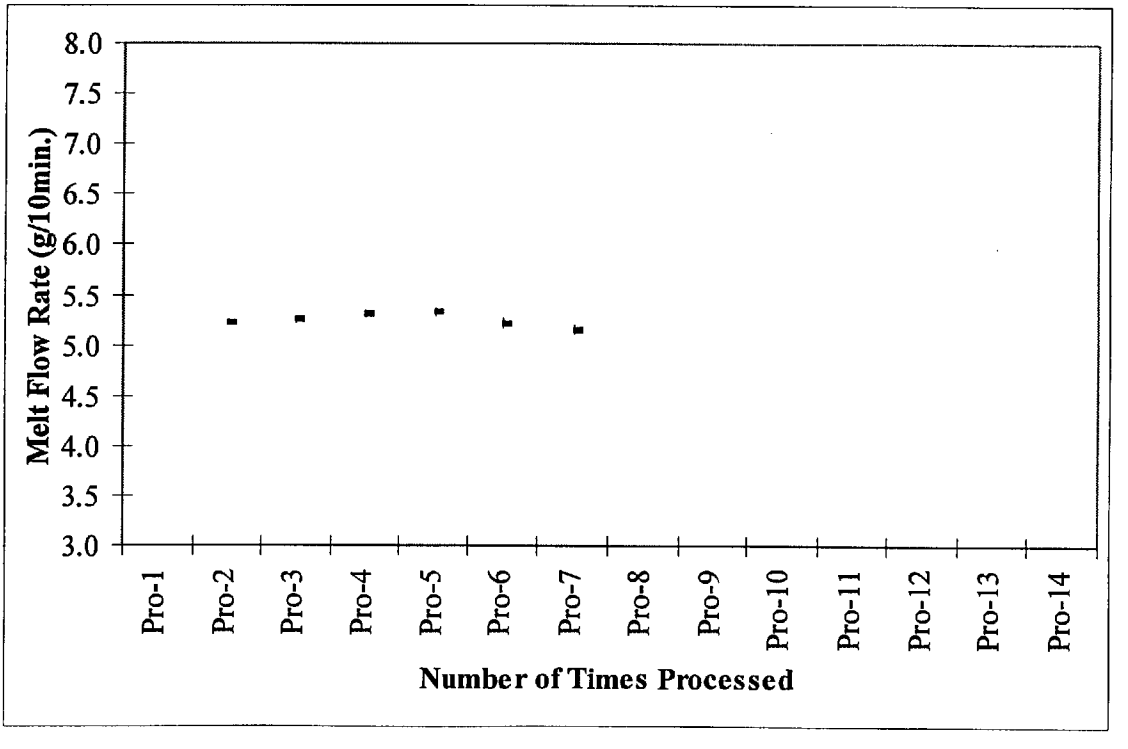
APPENDIX 5.1

MELT FLOW RATE (MFR) OF THE HDPEs RECYCLED AND REPROCESSED IN DHAKA

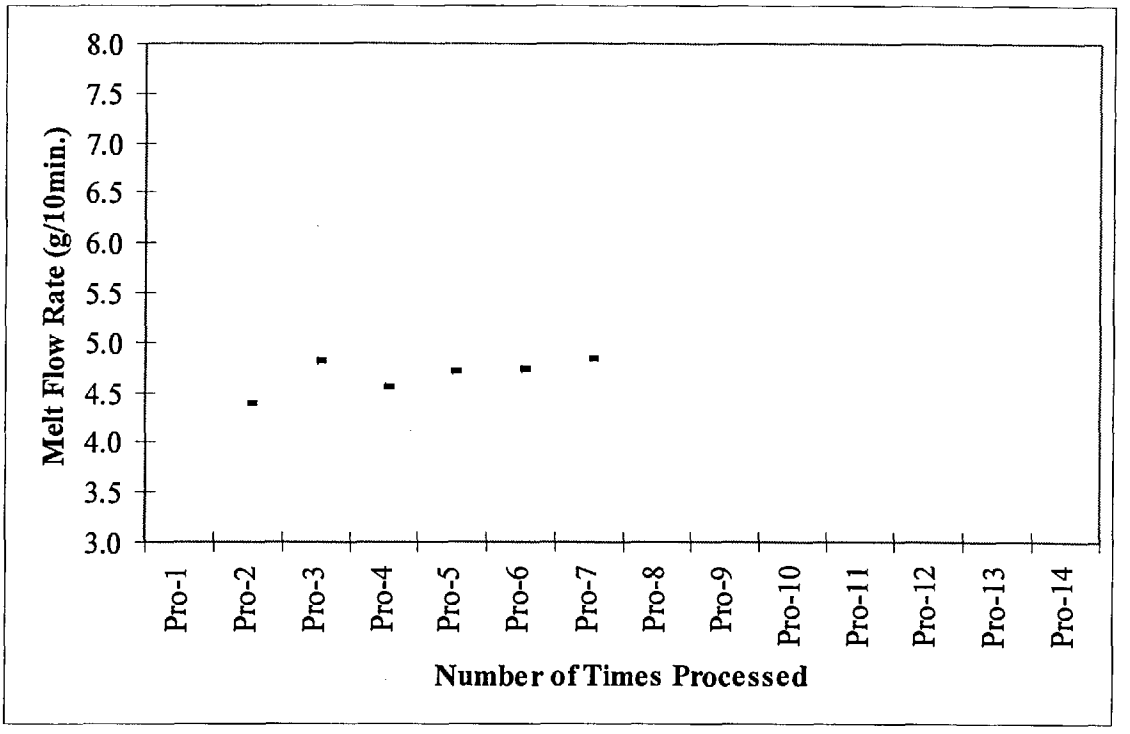
Appendix 5.1.1: MFR vs. successive number of processings of Translucent Flakes, Single Grade, Long Life,(2B)/1



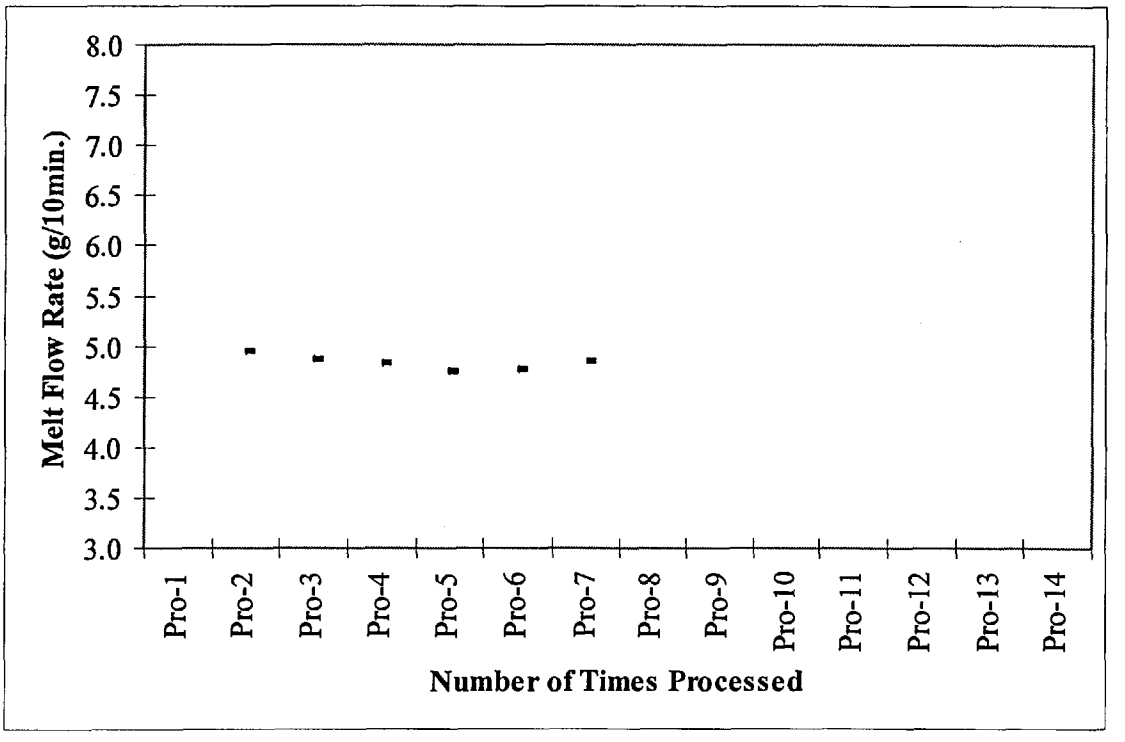
Appendix 5.1.2: MFR vs. successive number of processings of Translucent Pellets, Mixed Grade, (3A)/2.



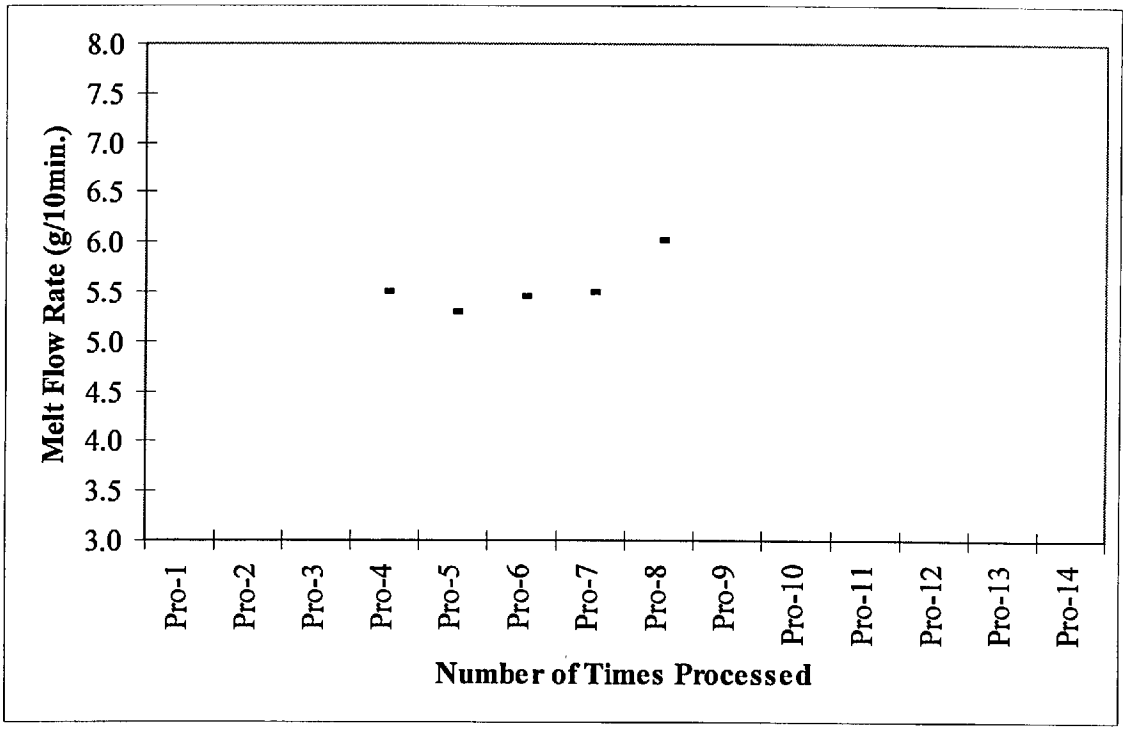
Appendix 5.1.3: MFR vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but double washed and colour flakes removed, (3B)/2



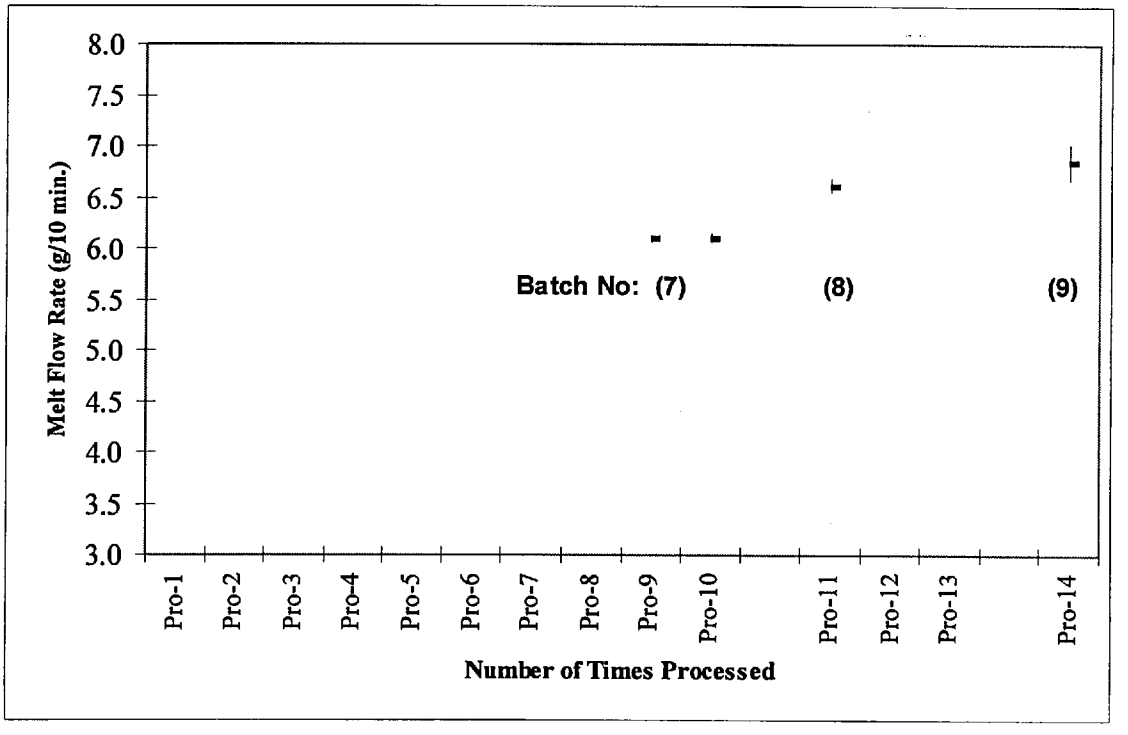
Appendix 5.1.4: MFR vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but chaff won, (3C)/2.



Appendix 5.1.5: MFR vs. successive number of processings of Brown Coloured Granules (5)/4.



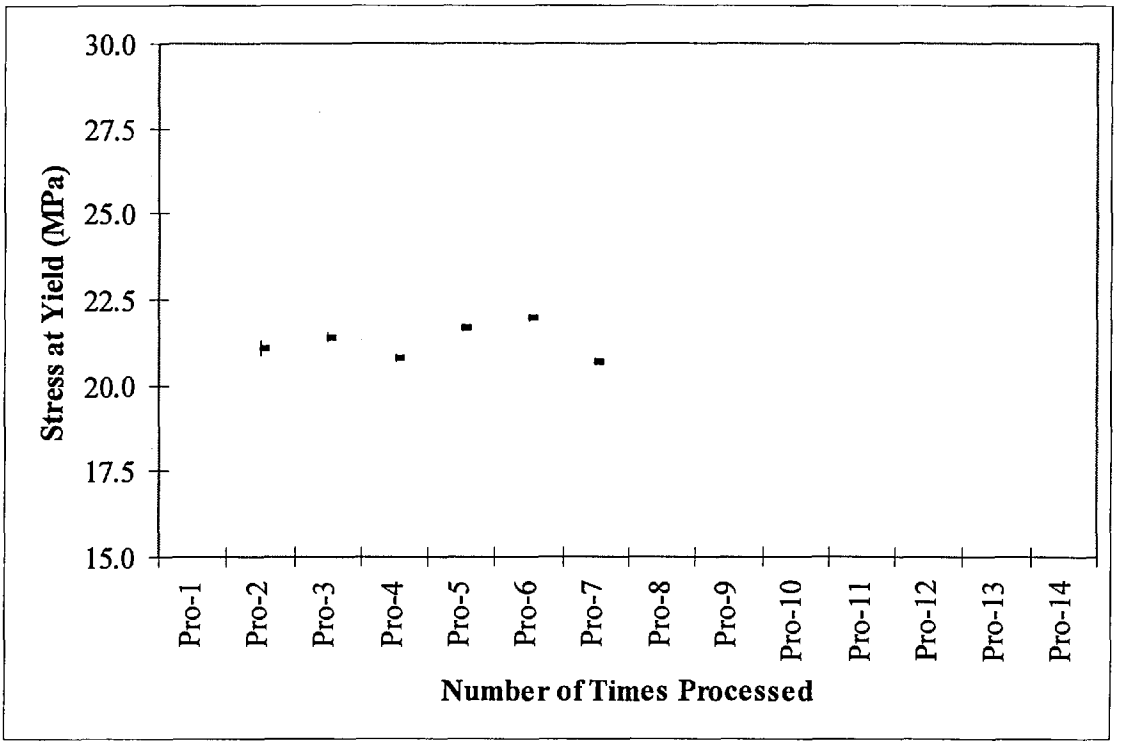
Appendix 5.1.6: MFR vs. successive number of processings of Black (7)/8, Dull-Black (8)/10, and Very Dull-Black (9)/13.



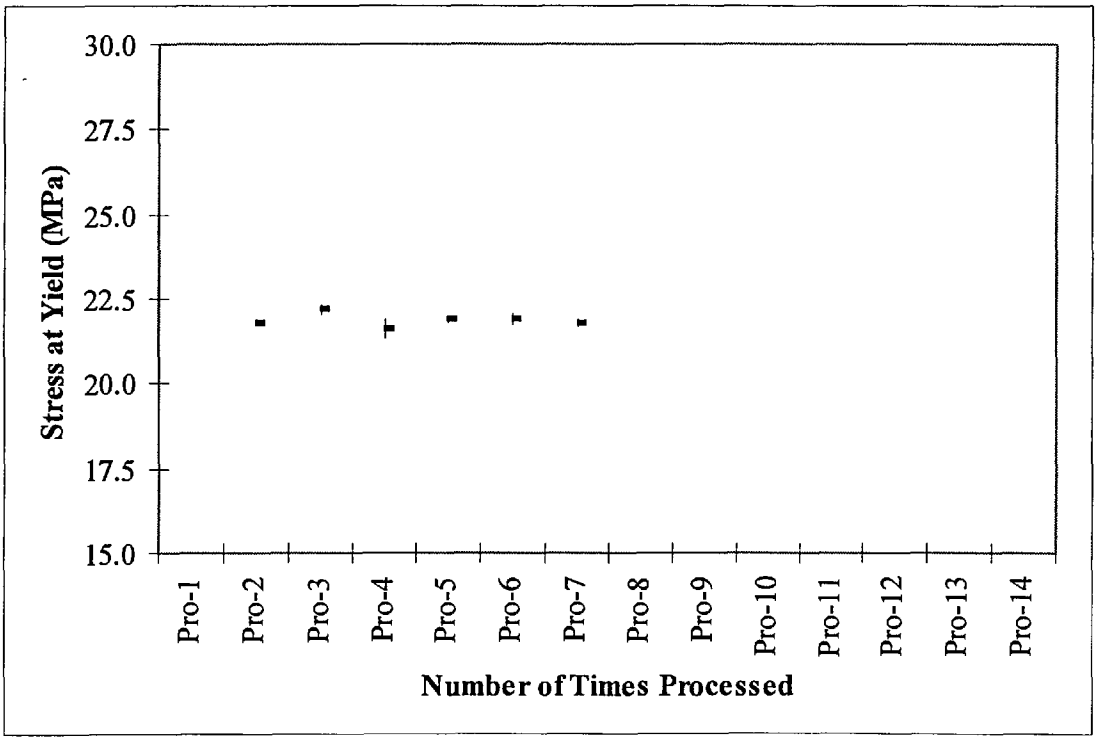
APPENDIX 5.2

STRESS AT YIELD VALUES OF THE HDPEs RECYCLED AND REPROCESSED IN DHAKA

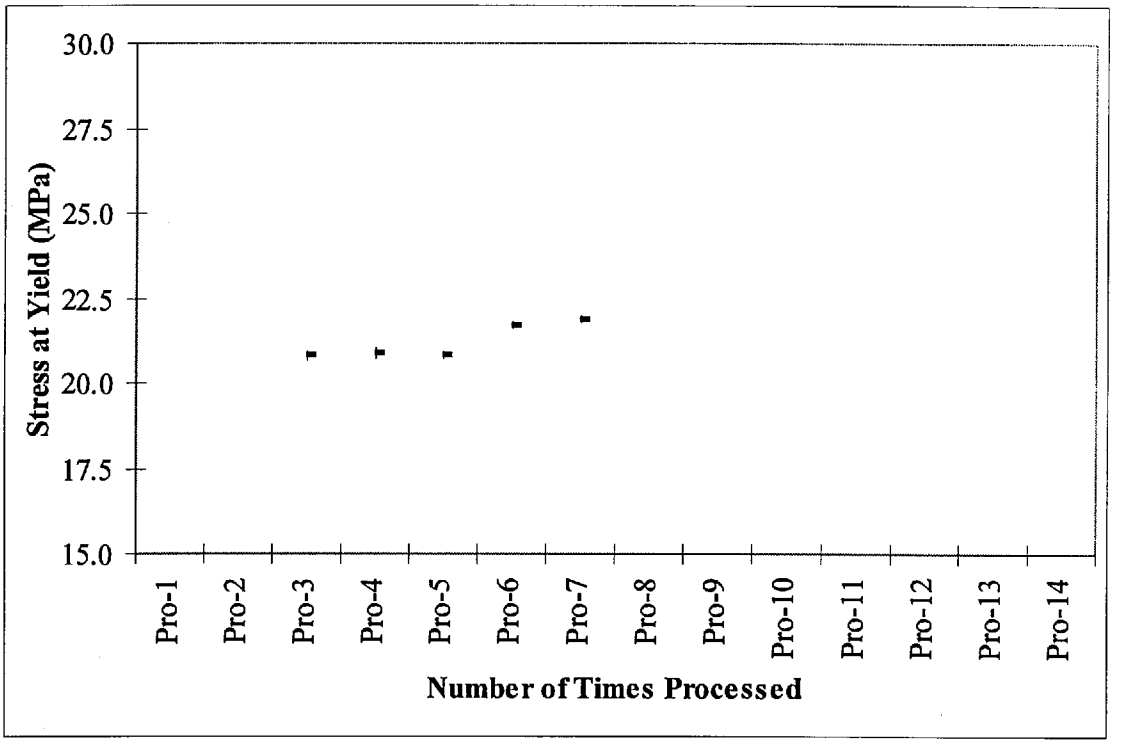
Appendix 5.2.1: Stress at Yield vs. successive number of processings of Translucent Flakes, Single Grade, Short Life,(2A)/1.



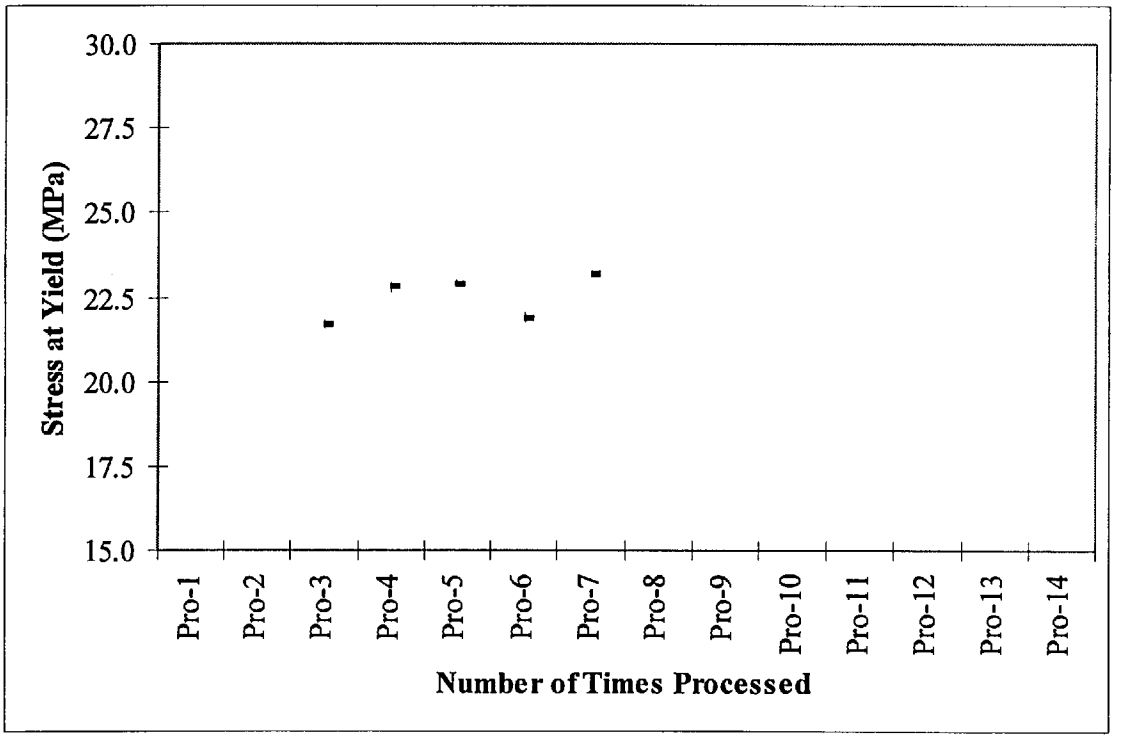
Appendix 5.2.2: Stress at Yield vs. successive number of processings of Translucent Flakes, Single Grade, Long Life,(2B)/1.



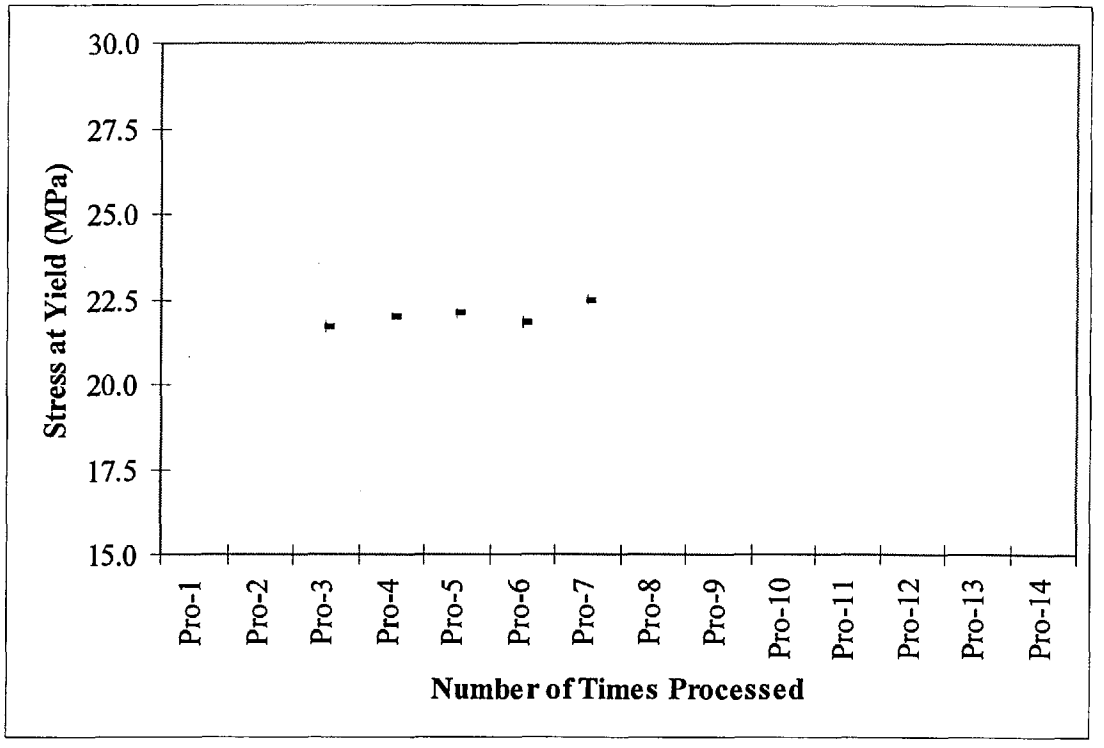
Appendix 5.2.3: Stress at Yield vs. successive number of processings of Translucent Pellets, Mixed Grade, (3A)/2.



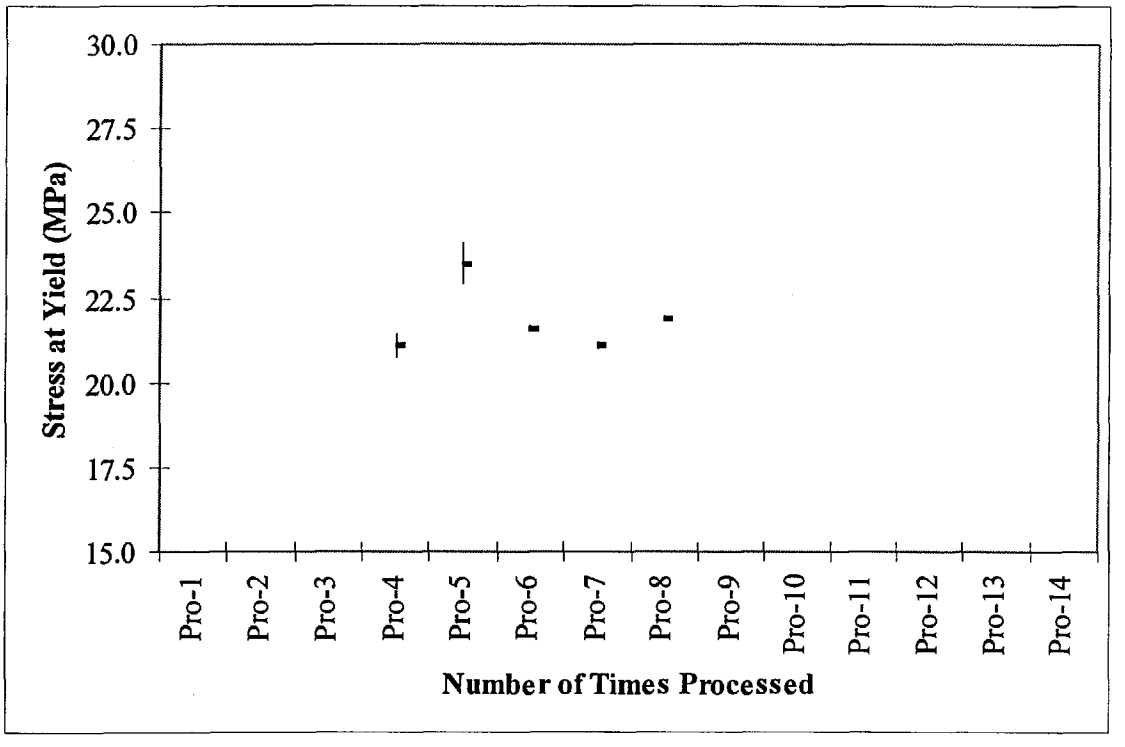
Appendix 5.2.4: Stress at Yield vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but double washed and colour flakes removed, (3B)/2.



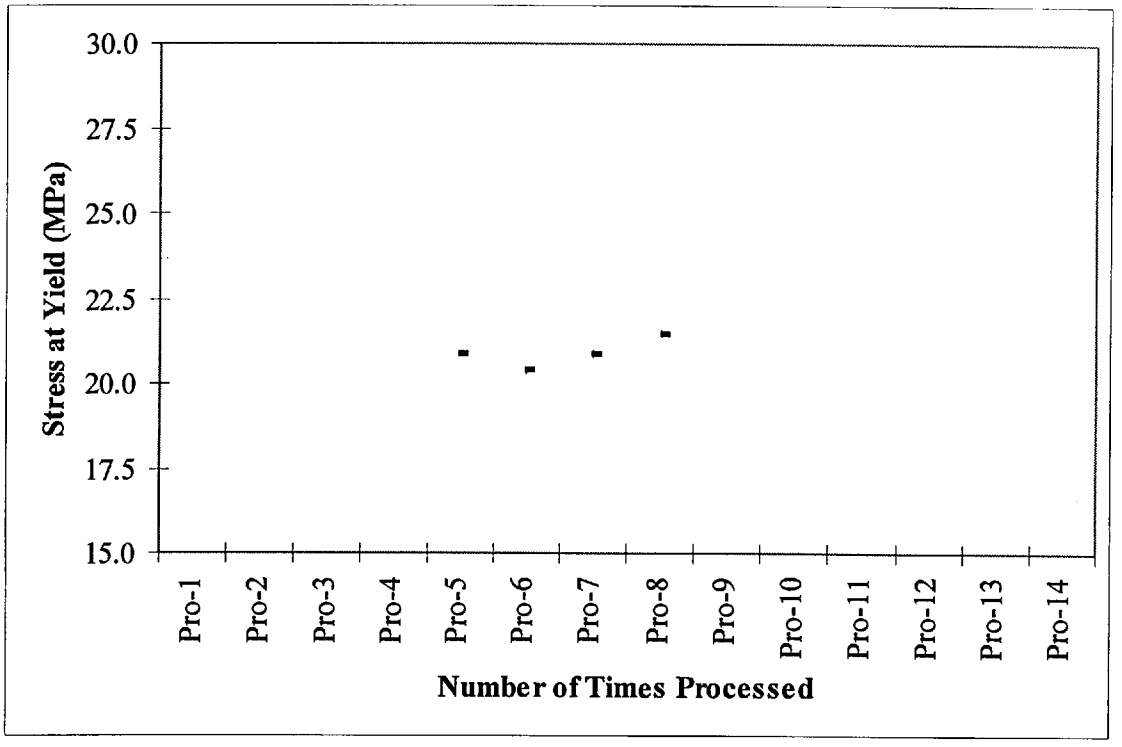
Appendix 5.2.5: Stress at Yield vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but chaff won, (3C)/2.



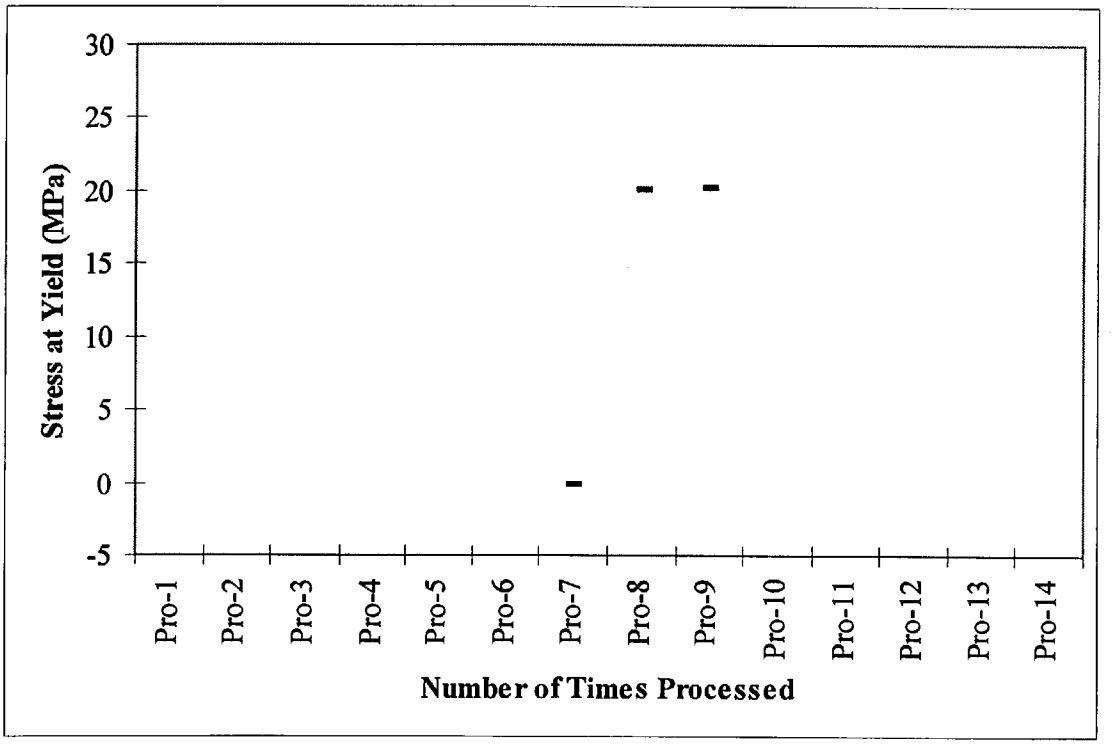
Appendix 5.2.6: Stress at Yield vs. successive number of processings of Milky Coloured Pellets (4)/3.



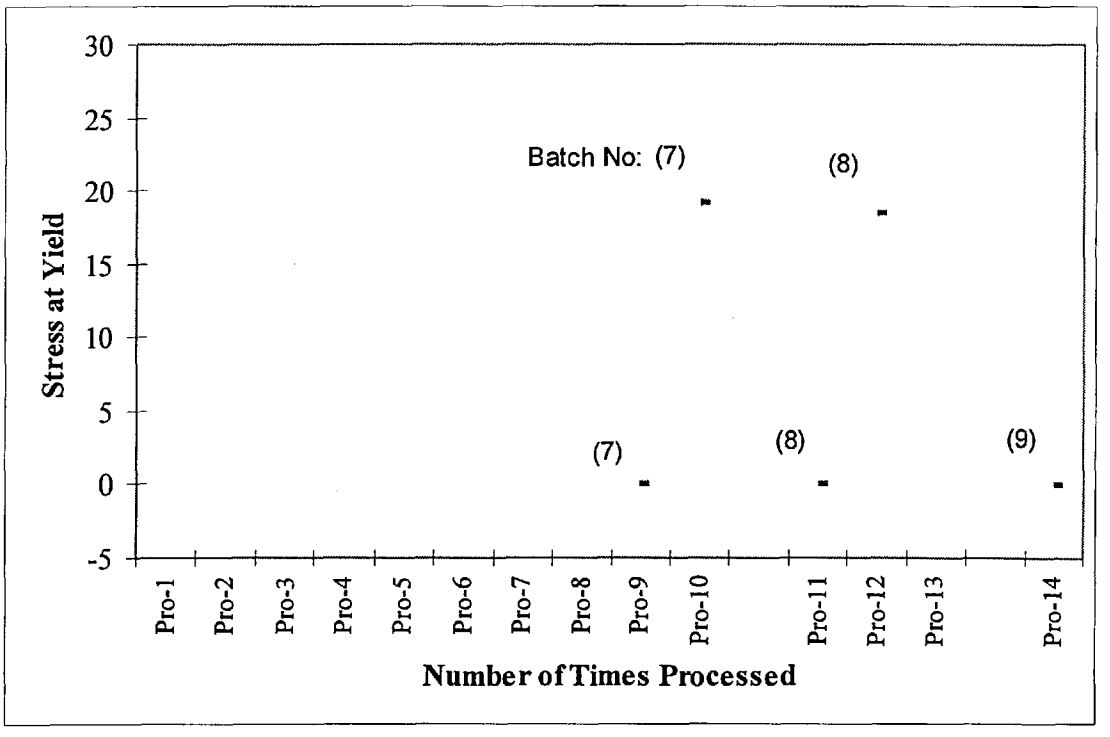
Appendix 5.2.7: Stress at Yield vs. successive number of processings of Brown Coloured Granules (5)/4.



Appendix 5.2.8: Stress at Yield vs. successive number of processings of Dull-Brown Coloured Granules (6)/6.



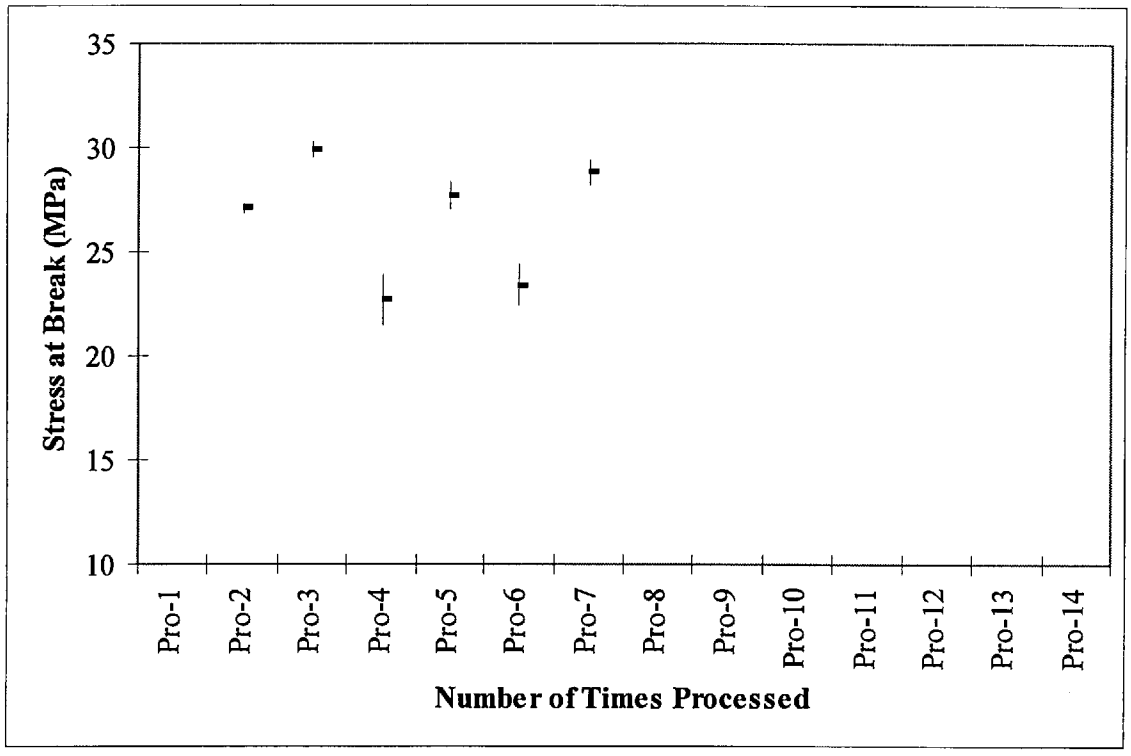
Appendix 5.2.9: Stress at Yield vs. successive number of processings of Black (7)/8, Dull-Black (8)/10, and Very Dull-Black (9)/13.



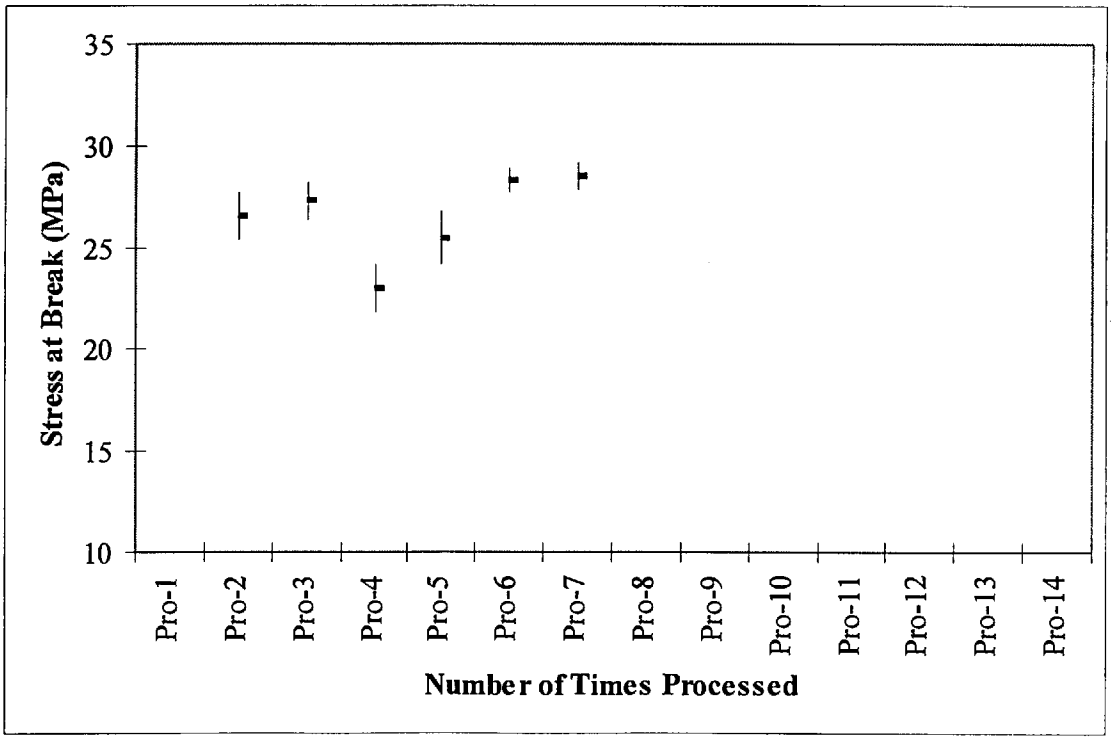
APPENDIX 5.3

STRESS AT BREAK VALUES OF THE HDPEs RECYCLED AND REPROCESSED IN DHAKA

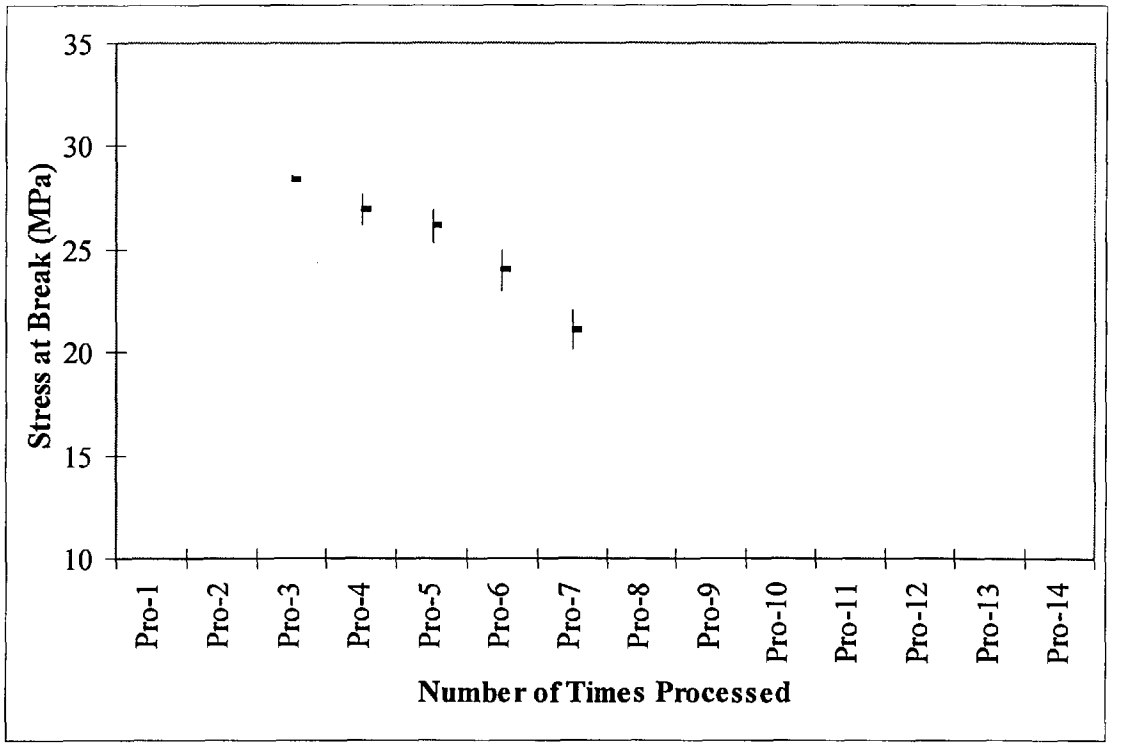
Appendix 5.3.1: Stress at Break vs. successive number of processings of Translucent Flakes, Single Grade, Short Life,(2A)/1.



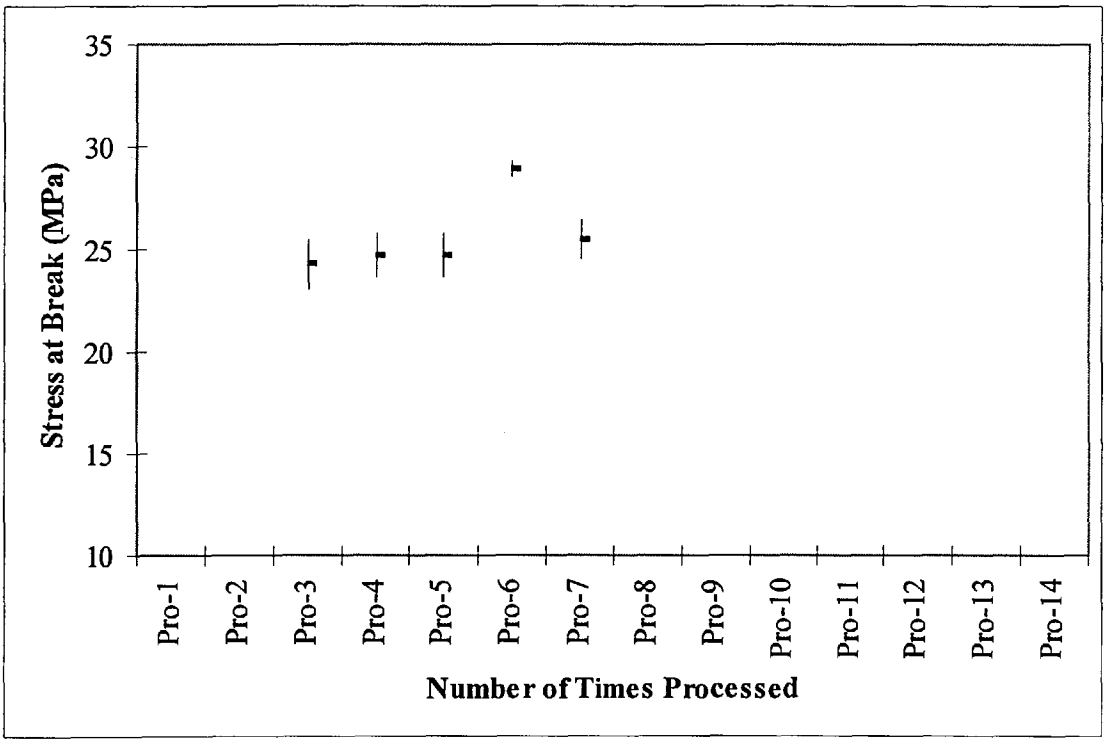
Appendix 5.3.2: Stress at Break vs. successive number of processings of Translucent Flakes, Single Grade, Long Life,(2B)/1.



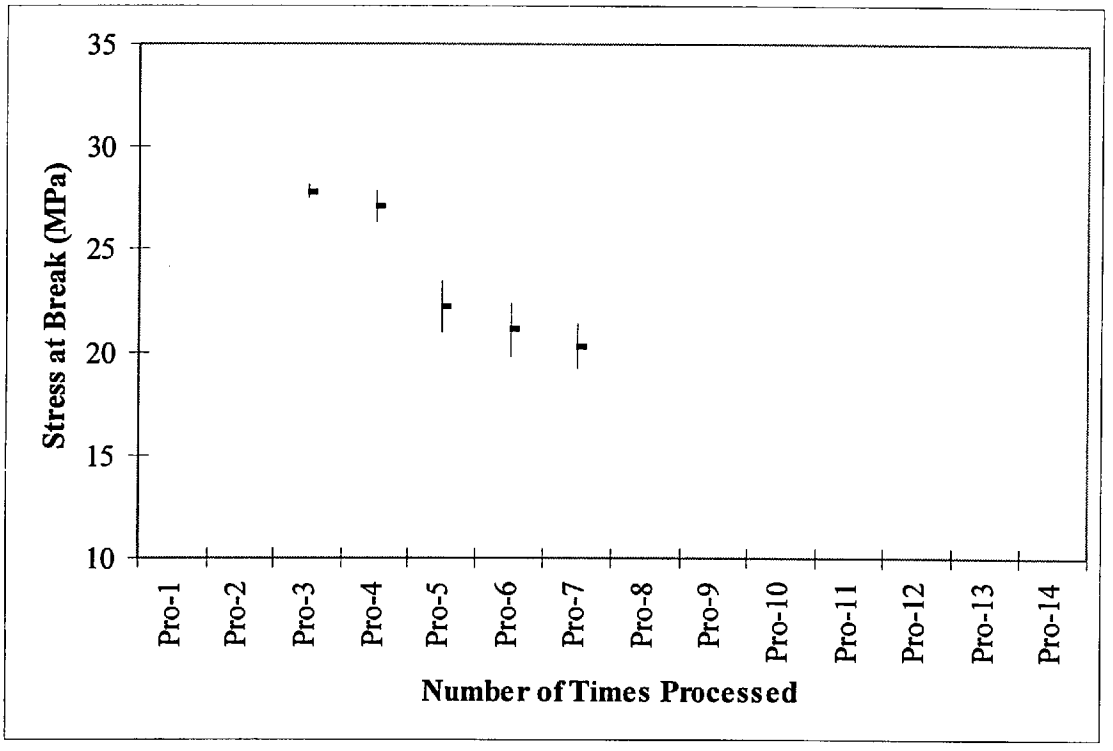
Appendix 5.3.3: Stress at Break vs. successive number of processings of Translucent Pellets, Mixed Grade, (3A)/2.



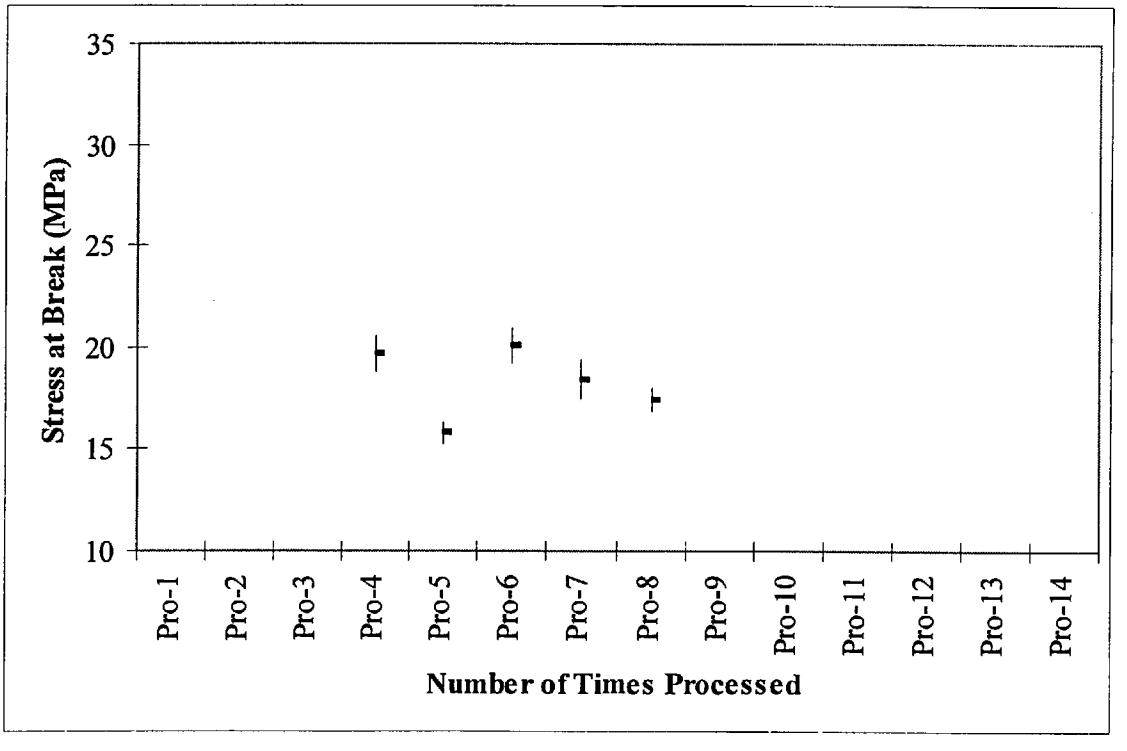
Appendix 5.3.4: Stress at Break vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but double washed and colour flakes removed, (3B)/2.



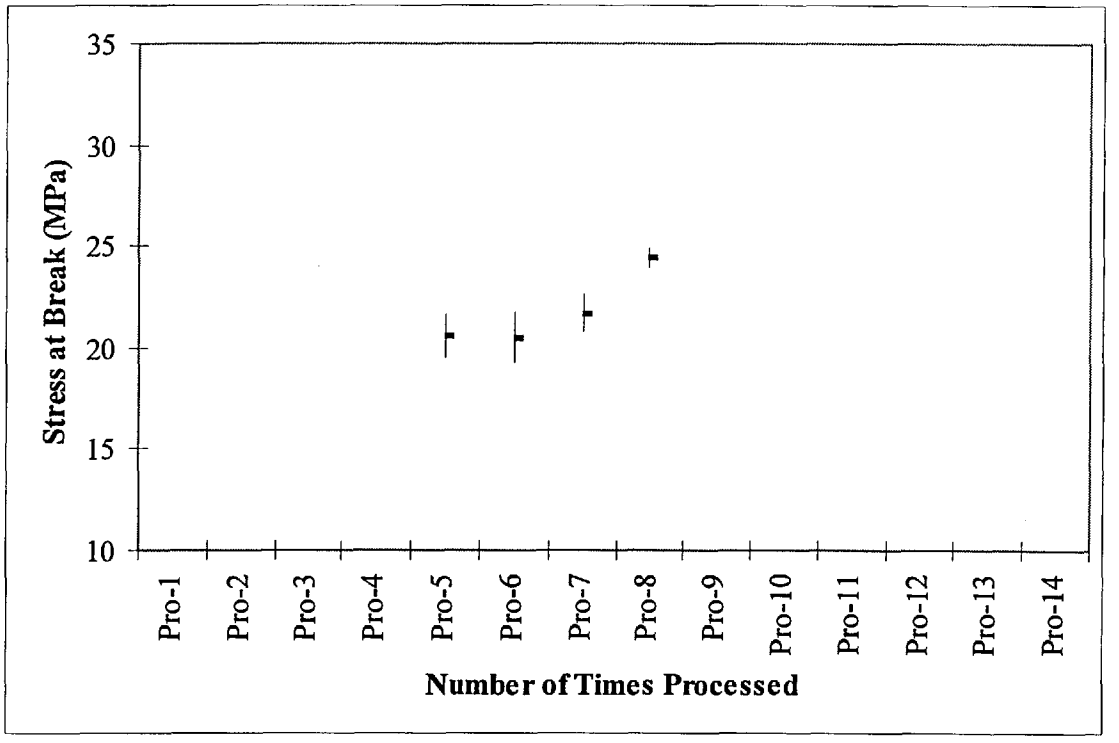
Appendix 5.3.5: Stress at Break vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but chaff won, (3C)/2.



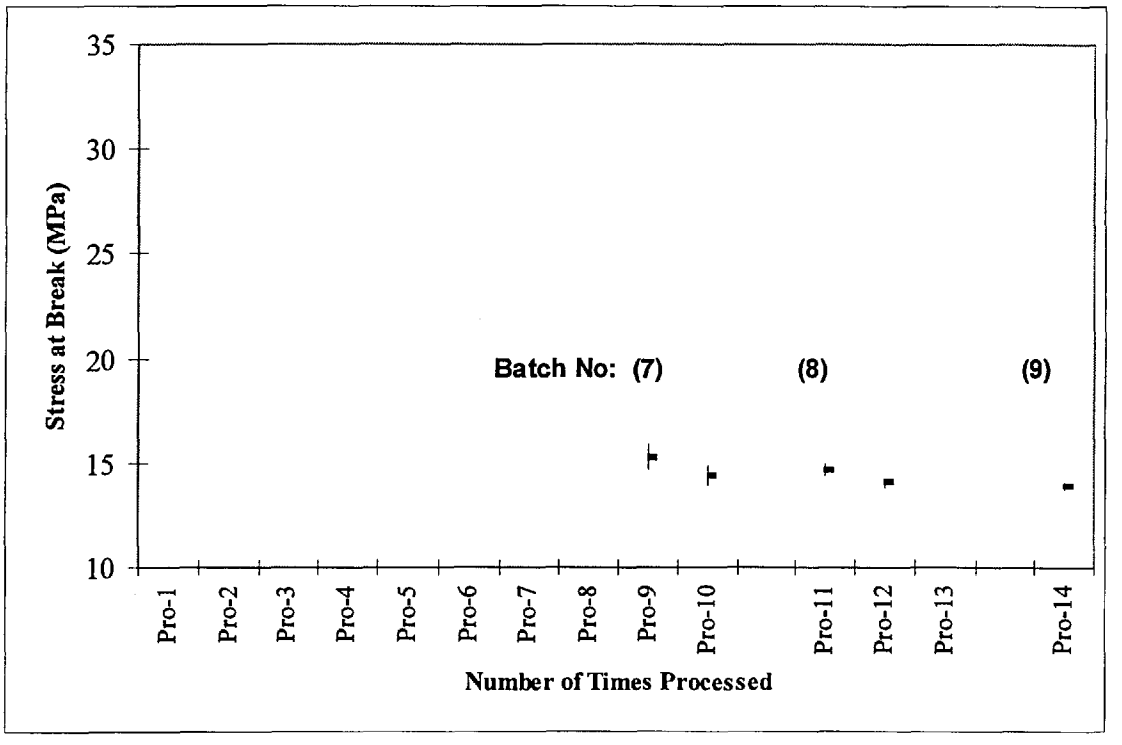
Appendix 5.3.6: Stress at Break vs. successive number of processings of Milky Coloured Pellets (4)/3.



Appendix 5.3.7: Stress at Break vs. successive number of processings of Brown Coloured Granules (5)/4.



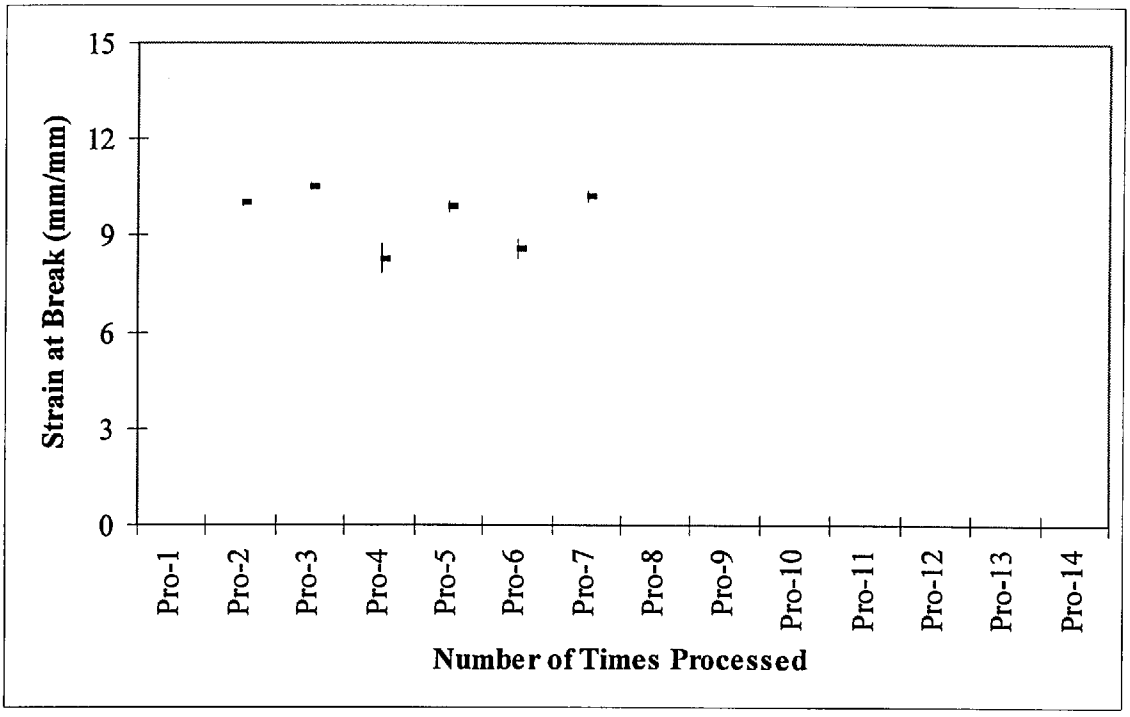
Appendix 5.3.8: Stress at Break vs. successive number of processings of Black (7)/8,: Dull-Black (8)/10, and Very Dull-Black (9)/13.



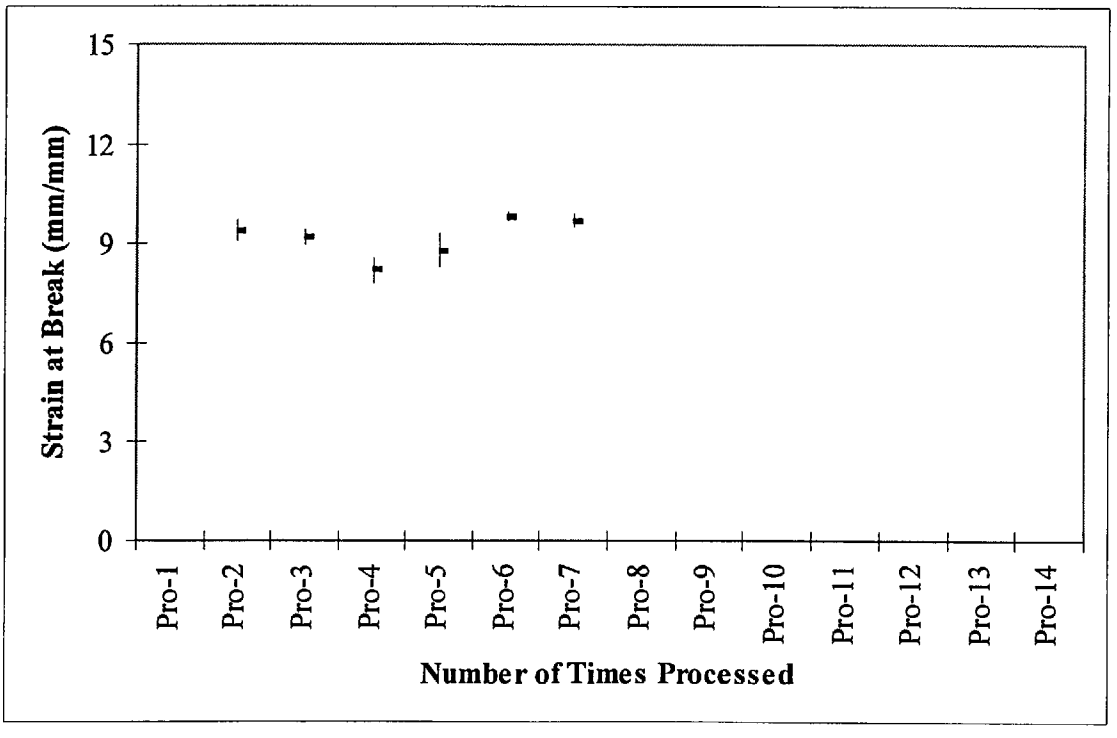
APPENDIX 5.4

STRAIN AT BREAK VALUES OF THE HDPEs RECYCLED AND REPROCESSED IN DHAKA

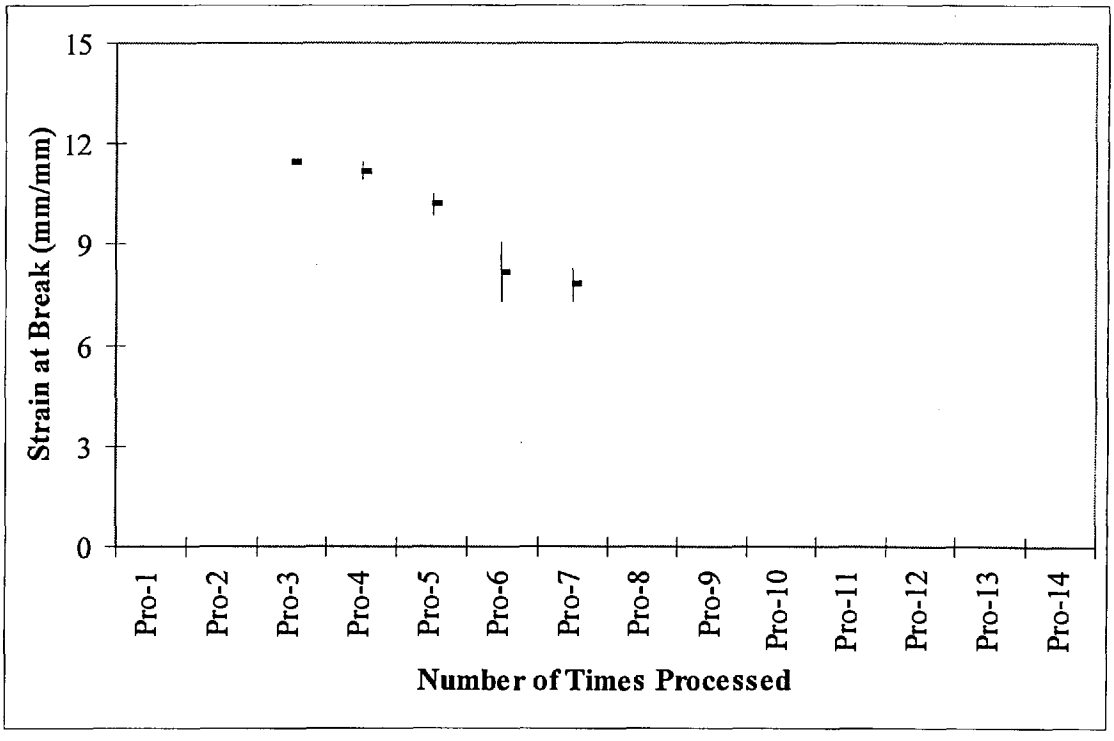
Appendix 5.4.1: Strain at Break vs. successive number of processings of Translucent Flakes, Single Grade, Short Life,(2A)/1.



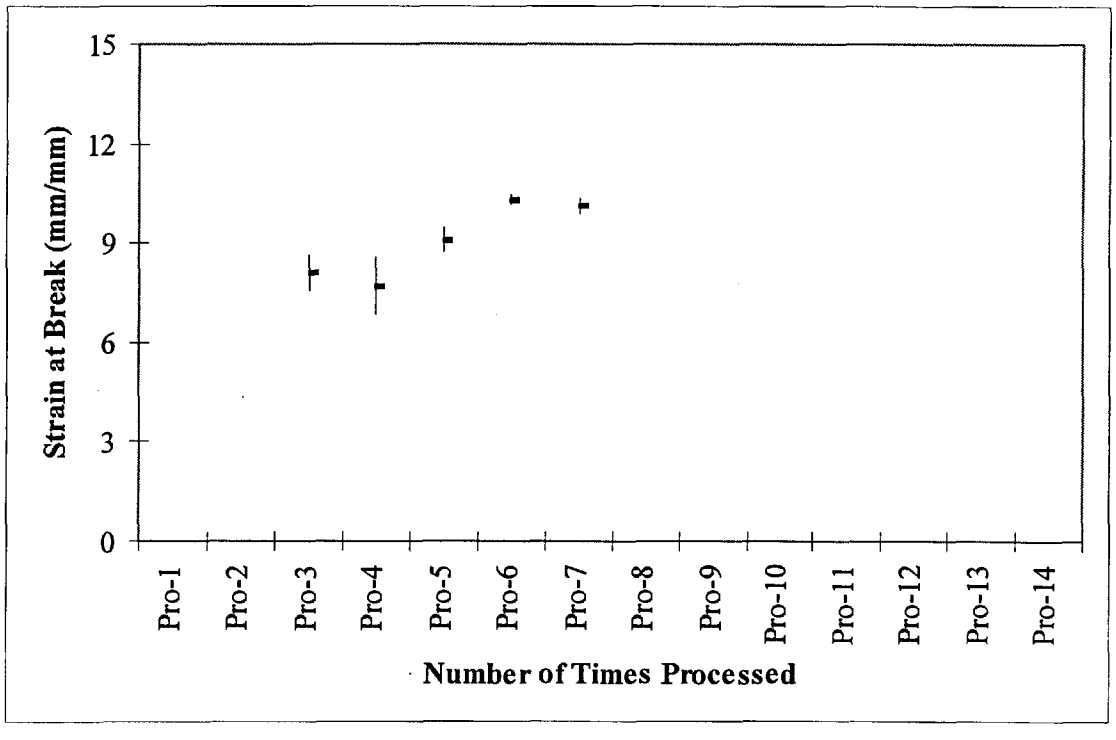
Appendix 5.4.2: Strain at Break vs. successive number of processings of Translucent Flakes, Single Grade, Long Life,(2B)/1.



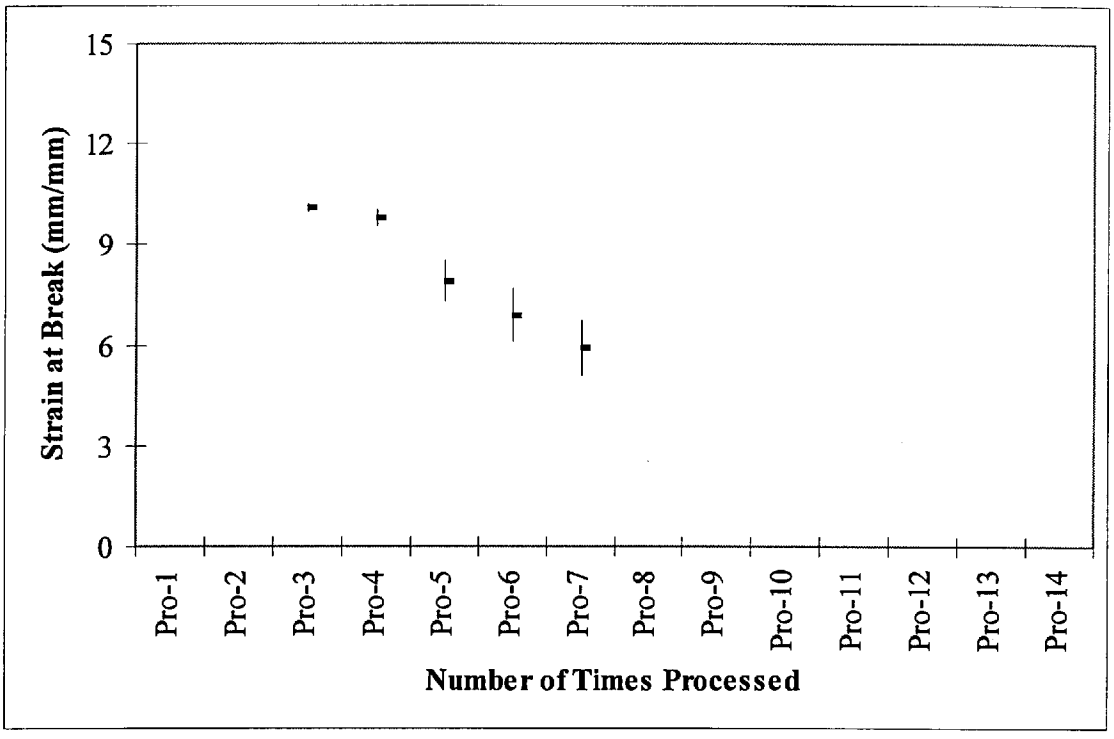
Appendix 5.4.3: Strain at Break vs. successive number of processings of Translucent Pellets, Mixed Grade, (3A)/2.



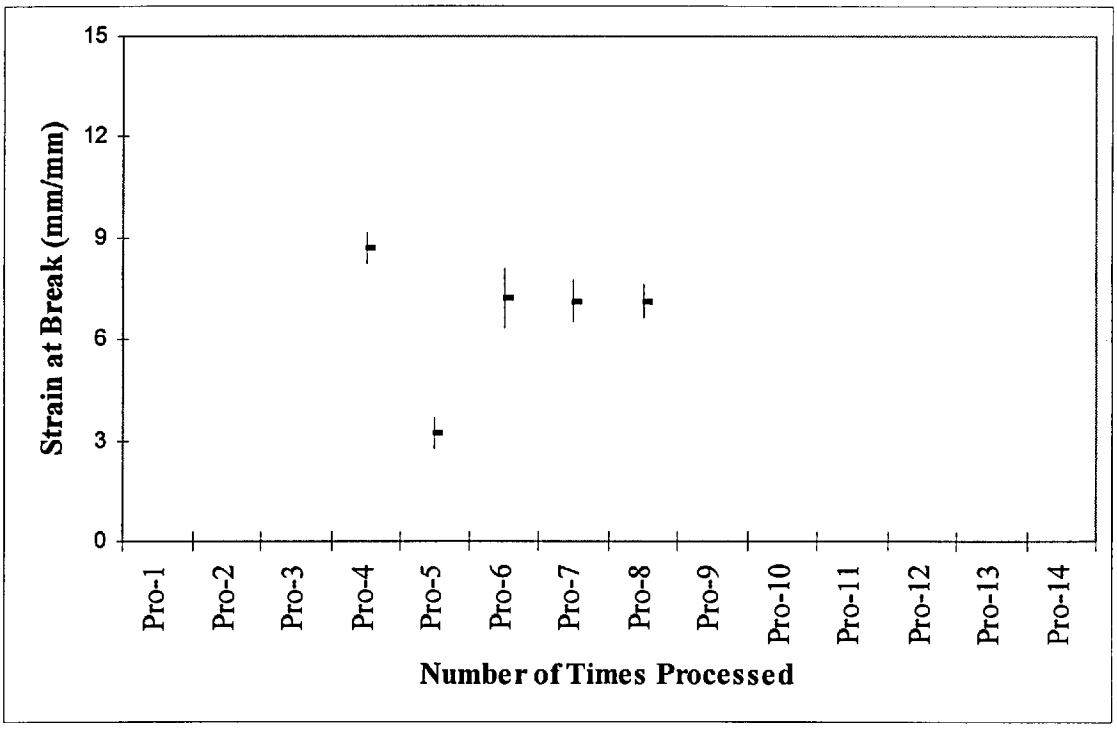
Appendix 5.4.4: Strain at Break vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but double washed and colour flakes removed, (3B)/2.



Appendix 5.4.5: Strain at Break vs. successive number of processings of a Derivative of the Translucent Pellets-(3A)/2, but chaff won, (3C)/2.



Appendix 5.4.6: Stress at Yield vs. successive number of processings of Milky Coloured Pellets (4)/3.



APPENDIX 6.1

PROGRAMMING MATHEMATICAL MODELS USING FORTRAN COMPUTER LANGUAGE

A/ Diagrams Describing the Concepts Used in Programming the Models

Diagram A.1: Graphical illustration of the concepts included in the mathematical modelling.

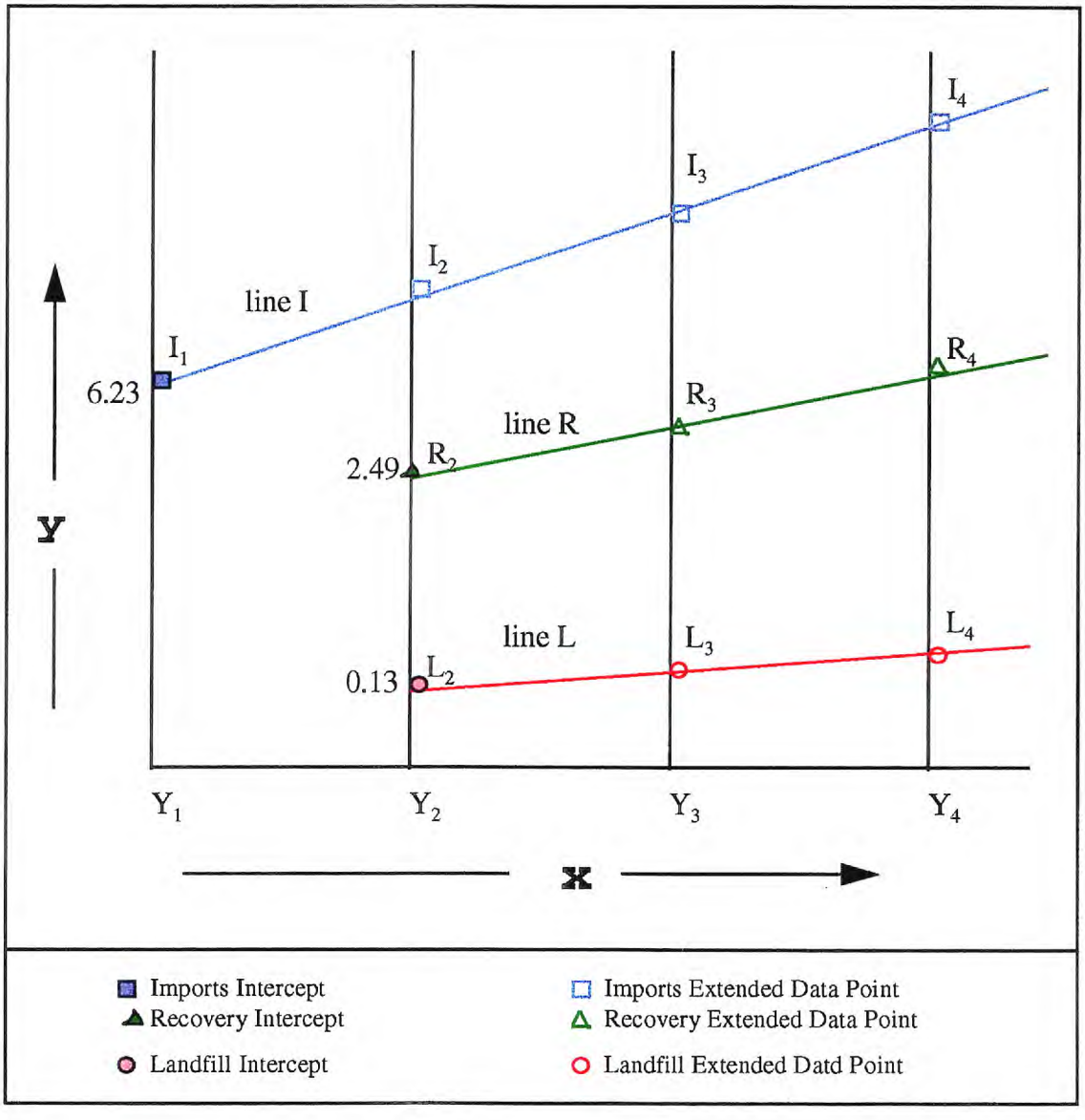
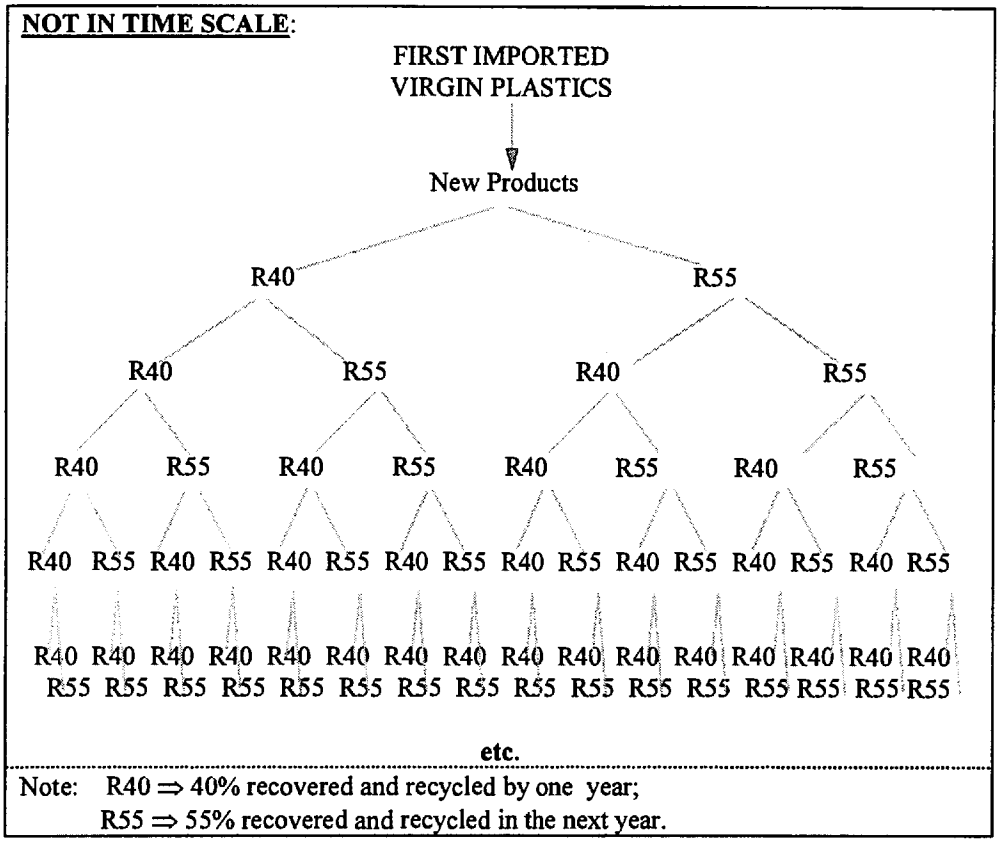
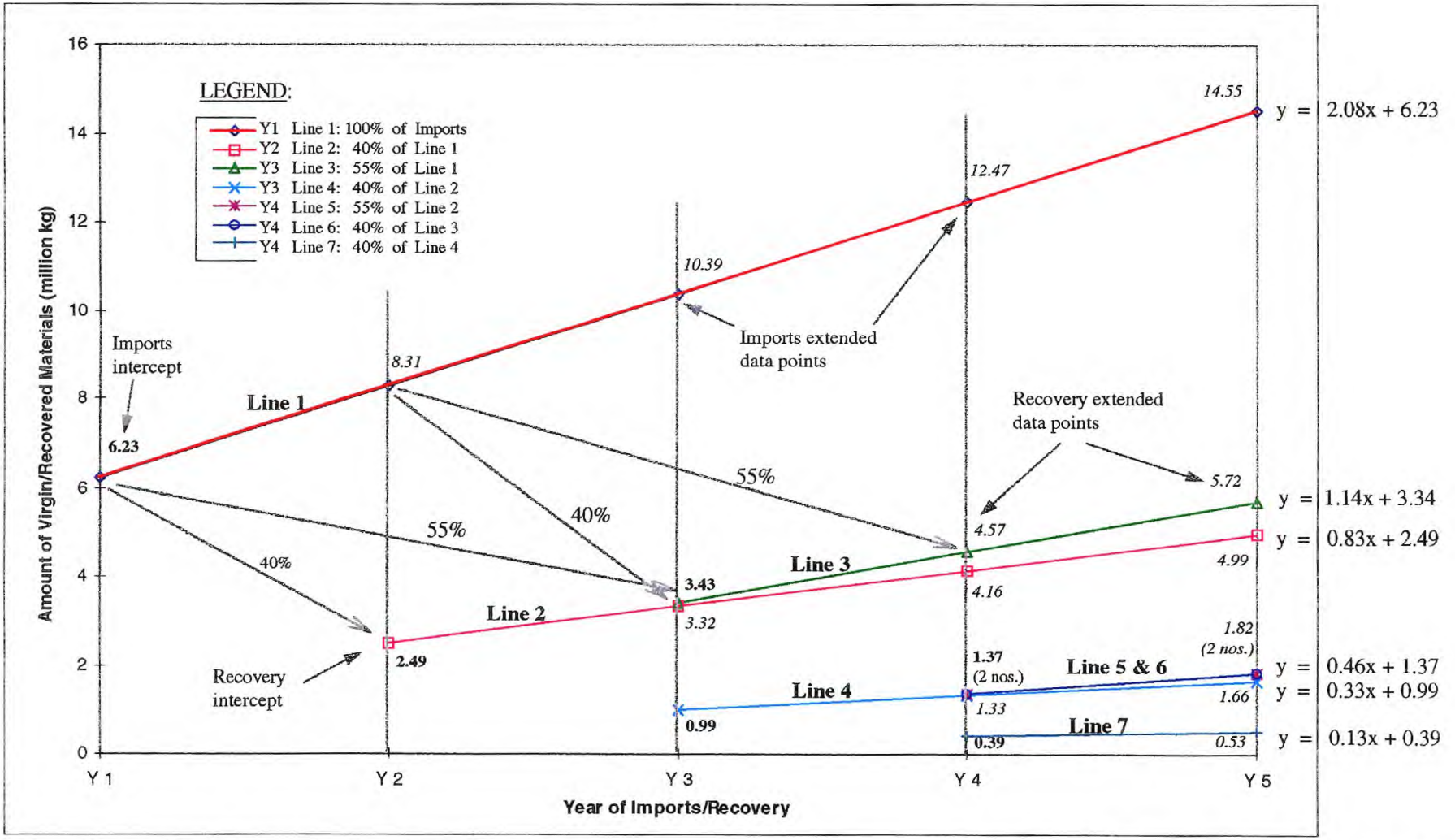


Diagram A.2: Geometrical expanding pattern of recovery percentages only, following the principle of the faster recovery scenario shown in Figure 6.2 (in Chapter 6).



Notes for Diagram A.2: Following the example of faster recovery scenario in Figure 6.2 (in Chapter 6) starting with only one initial lot of PE in the Y_1, the number of recovery percentages in the subsequent years is expanding geometrically as a chain effect as shown in this Diagram A.2. Similarly, in the case of other lots of PE imported in the subsequent years (Y_2, Y_3, Y_4, ...), the same patterns of expansion in their own sets of recovery and landfilling percentages will occur and overlap each other. These imply that, within a low number of successive recycling steps, the number of branches growing out of the single virgin material becomes very large.

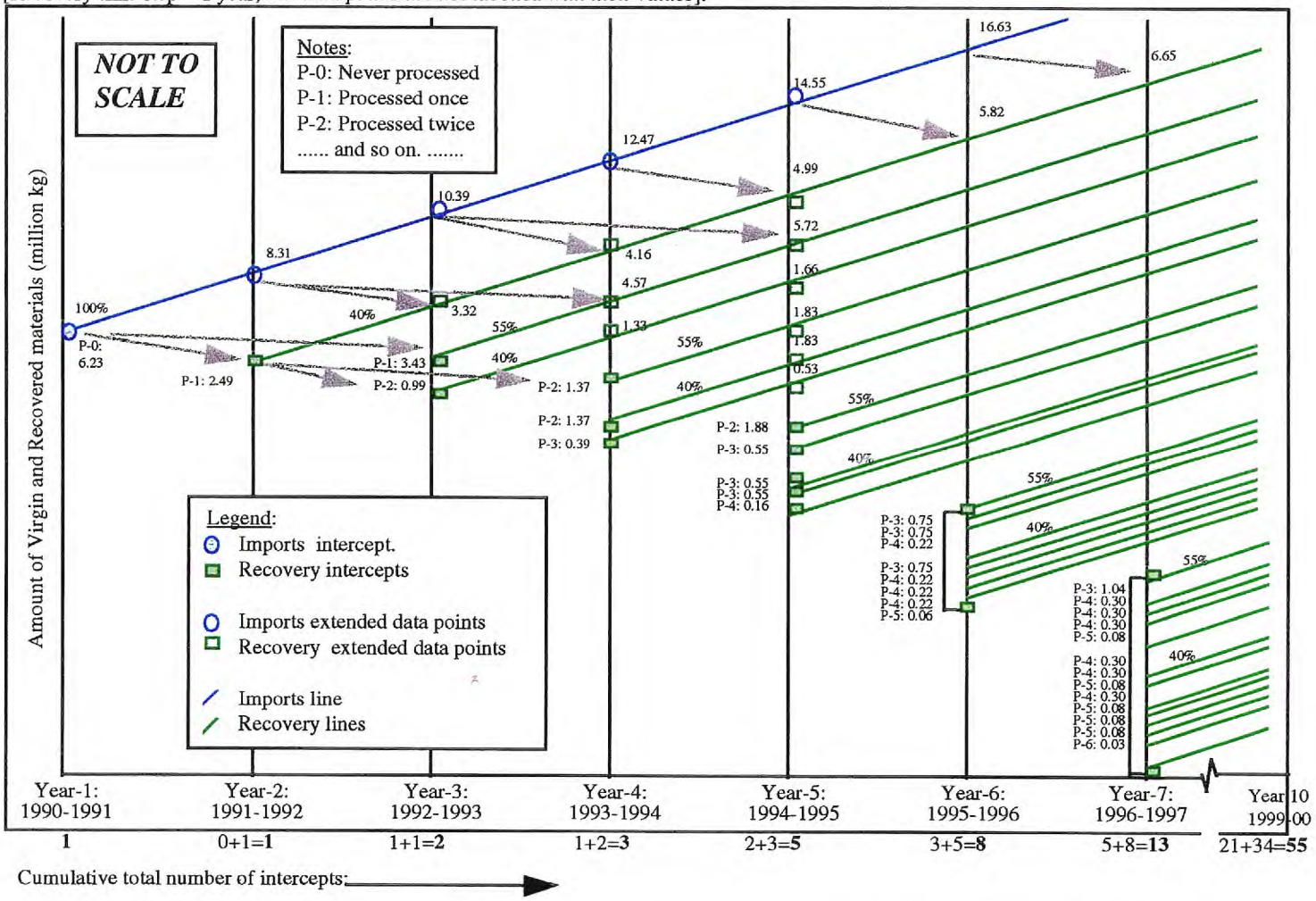
Diagram A.3: Graphical presentation of faster **recovery** scenario of Polyethylene [Time step = 1 year].



Notes for Diagram A.3: In order to clarify matters, Figure 6.2 is graphically presented in Diagram A.3 by plotting the magnitudes of import and recovery percentages in the form of *'intercept values'* at the corresponding year of recovery. This Diagram A.3 forms the initial structure of faster recovery scenario model which has started with an '**imports intercept**' value of 6.23 Mkg at the base year (Y_1) being the intercept of the linear Equation 6.1.

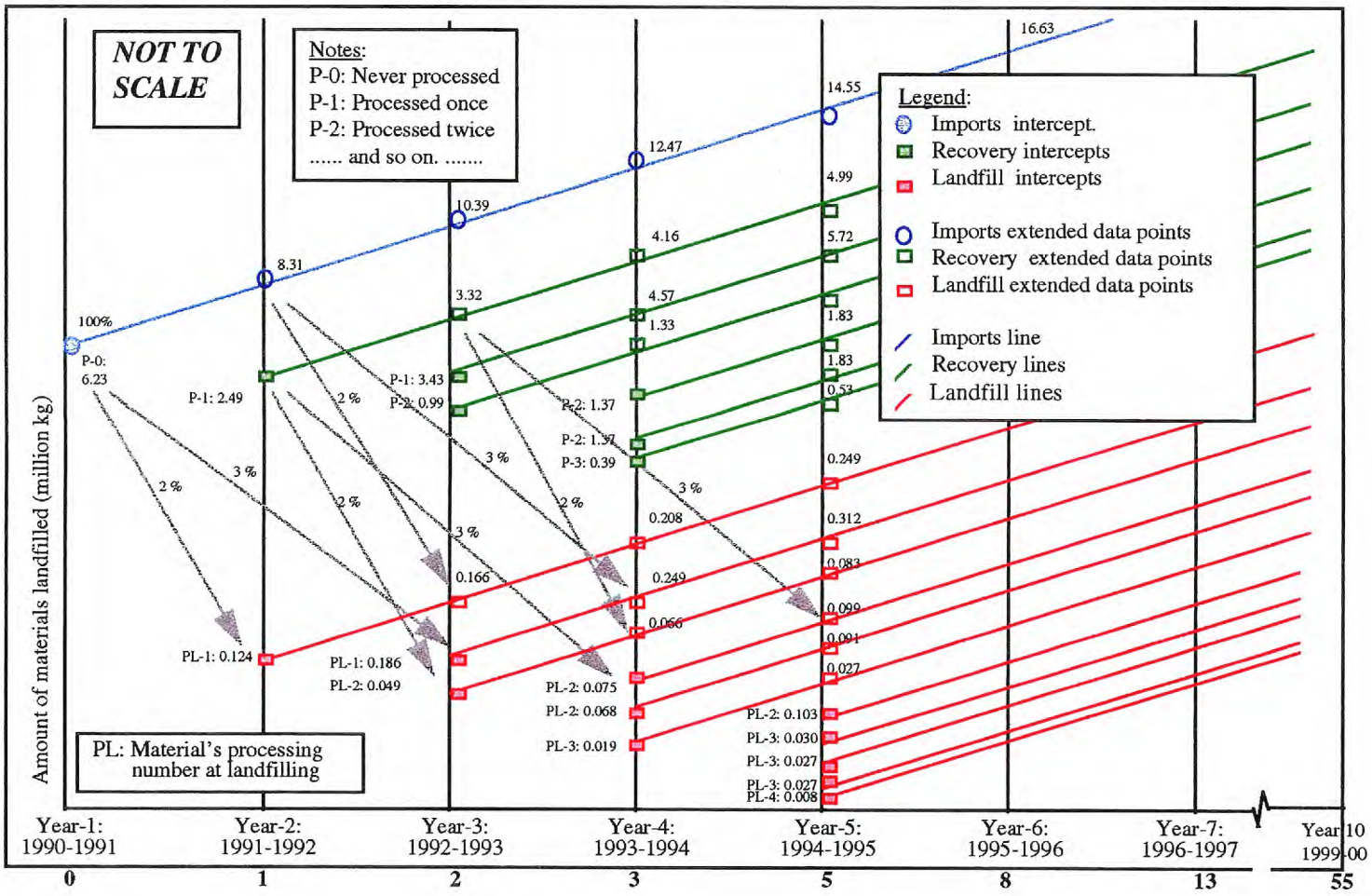
Diagram A.4: Faster **recovery** scenario model: Amount of virgin and recycled Polyethylene (PE) - HDPE & LDPE.

[Recovery time step = 1 year; *All data points are not labelled with their values*].



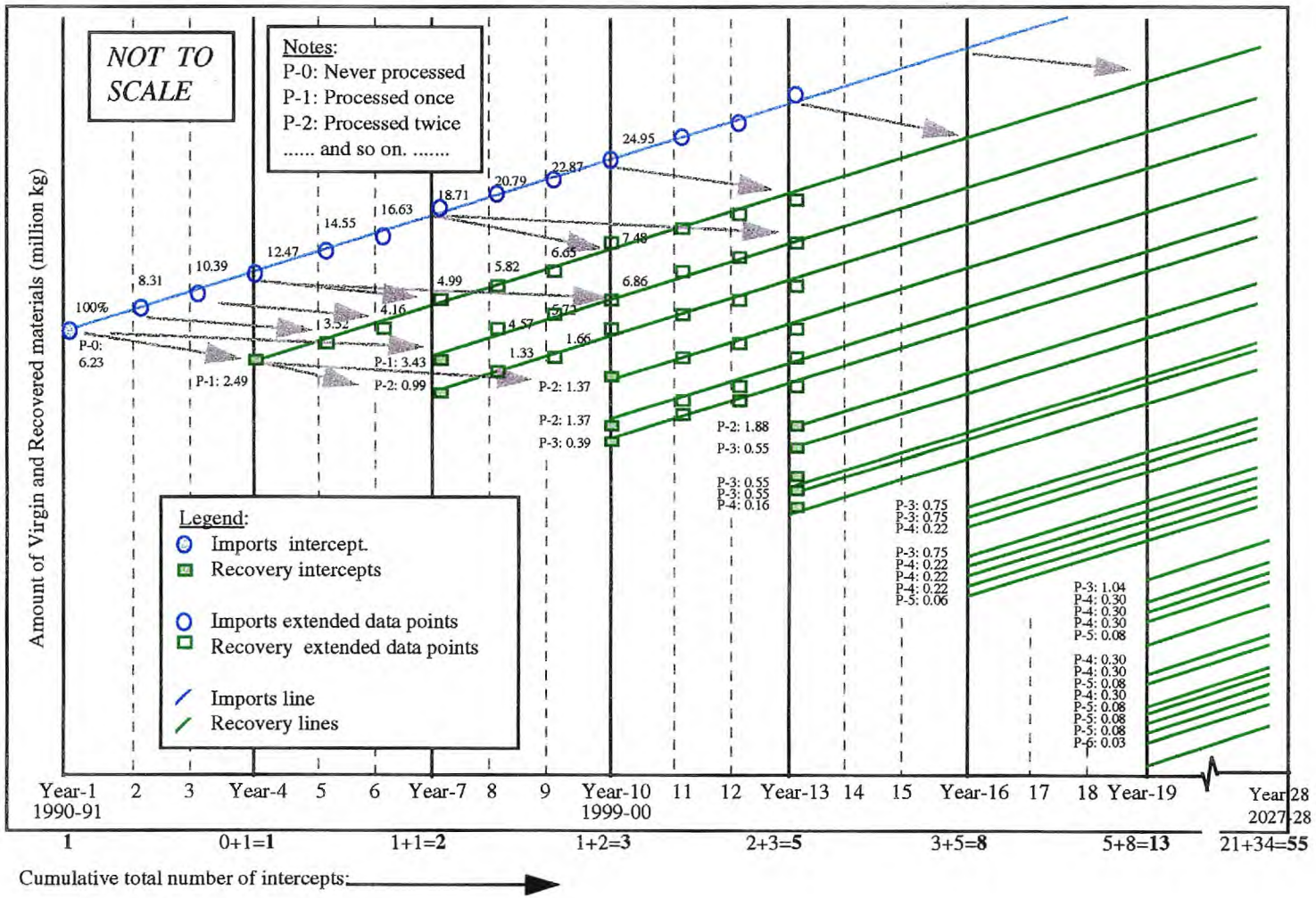
Notes: Following this cumulatively increasing pattern of new recovery intercepts appearing each year, computationally efficient models have been developed to determine the total number of these intercepts in a year, and the values of each individual intercept points on the y-axis at the corresponding year. These mathematical models are capable of identifying, storing and using repeatedly all these numbers and values of each batch of recovered plastics by identifying them in terms of their 'year of recovery', 'number of processings', and 'category of recovery percentages' (either 40% or 55%). Similarly, these models are also robust enough to identify, store and calculate the total number and values of 'extended data points' in each year, against their corresponding 'year of recovery', 'number of processings' and 'category of recovery percentages'. Note that both the 'number of processings' and 'category of recovery percentages' of 'extended data points' on a particular straight line are the same as those of the intercept of that line.

Diagram A.5: Faster **Landfilling** scenario model [Landfill time step = 01 year; *All data points are not labelled with their values*].



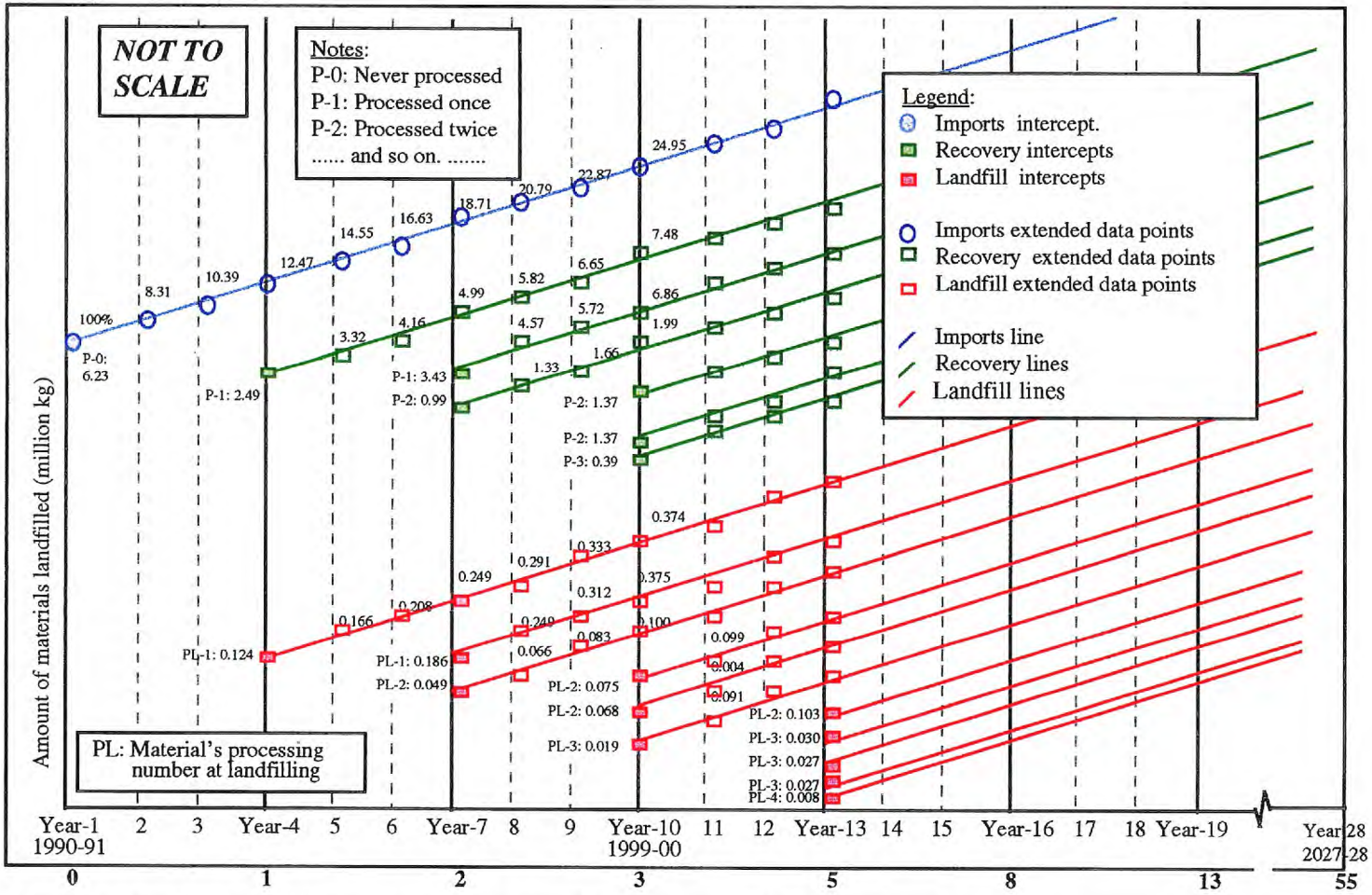
Notes: Under recovery scenario, 'recovery intercepts' and 'recovery extended data points' are calculated either as the 40% or 55% of those in the previous years. However, under landfill scenario, the landfill intercepts at any year, j, are obtained taking either 2% and 3% of the imports/recovery intercepts (rather than landfill intercepts) in the previous years, Y_{j-1} and Y_{j-2}, respectively [Figures 6.2 (in Chapter 6) and Diagram A.5]. Note that except in Y_1 where amount of landfill is zero, the total number of 'landfill intercepts' derived at any year (starting from Y_2) is equal to the total number of 'recovery intercepts' at that year. However, from Y_3 onward, the total number of 'landfill extended data points' on a y-axis at any year is less by one from the total number of the imports and recovery extended data points on the same axis in that particular year.

Diagram A.6: Slower **Recovery** scenario model [Recovery time step = 03 years; *All data points are not labelled with their values*].



Notes: Considering slow discarding and recovering scenarios, the current model is based on a '3 years time step' instead of '1 year time step'. Nevertheless, this model starts with the same ***'imports intercept'*** of 6.23 Mkg as in the faster recovery model and treats this amount as initial imports at the base year (Y_1).

Diagram A.7: Slower **Landfilling** scenario model [Landfilling time step = 03 years; *All data points are not labelled with their values*].



Notes: Total number of **landfill** intercepts at any year is equal to the total number of recovery intercepts at that year.

Notes: Under this slower scenario of landfilling, the 'year of landfilling' is the same as the 'year of recovery' in the slower recovery scenario model. As for the slower recovery scenario, 'landfill extended data points' are determined for each year, but 'landfill intercepts' are calculated after every '3 years time step'. Again, at any 'calculation year' the magnitude and number of the landfilling intercepts remain the same as in the faster landfill scenario model.

B/ Programme Written in FORTRAN:

```
C
C
C       VERY GENERALISED PROGRAMME  FOR MEASURING AMOUNT OF
C       DIFFERENT PLASTIC MATERIALS PRESENT IN A PARTICULAR YEAR
C       BY THEIR NUMBER OF TIMES PROCESSED (NPR) [In Million kg]:
c       ============================================================

C       VALID FILE: WITH ACTUAL "YEAR" AND "PROCESS NUMBERS"
c       Actual Year-0  ===> Year-1 or J =1, PROC-0 ===> NPR(1,1)=1
C       in this programme.
c       ..........................................................


C     //////////// PART 1:  DIMENSIONS AND INPUT DATA ////////////

C     DIMENSIONS ARE REQUIRED TO STORE INPUT AND OUTPUT VALUES

      IMPLICIT DOUBLE PRECISION (A-H, O-Z)

      DIMENSION  Y(25,5000), YY(35,25,5000), NPR(25,5000), SUM(25)
      DIMENSION  EX_Y(35,25,5000),  P_SUM(25,35),  Y_SUM(25)
      DIMENSION  SLP(25,5000), SLOPE(35,25,5000)


C     USER SUPPLIED DATA: OK FOR 19 YEARS >>> i.e. until 2008-2009

C     NO OF YEARS:
          JYEAR = 19

C     STARTING YEAR OF IMPORTATION
          N_YEAR = 1990

C    VALUE OF IMPORT IN STARTING YEAR
          YIMP = 6.23

C  APPROX. MAX. NUMBER OF PROCESSING APPEARED BY THE YEAR  "JYEAR"

          NPRO = 35

C APPROX. MAX. NUMBER OF RECOVERY INTERCEPT APPEARED BY THE YEAR
"JYEAR"

          IPROC = 3000


C     ////////////// PART 2: MODELLING STARTS ///////////////


         Y(1, 1) = YIMP

         DO 100   NP = 1, NPRO
         DO 100   J   = 1, JYEAR
         DO 100   I   = 1, IPROC

            YY(NP, J, I) = 0.0D0
            EX_Y(NP, J, I) = 0.0D0

100       CONTINUE
```

```
      NYEAR = N_YEAR + 1

      YY(1, 1, 1) = Y(1, 1)

      NPR(1, 1) = 1

          NLINE = 0.0

       SUM(1) = YY(1, 1, 1) + NLINE*2.08

             N_YEAR = 1991

             NYEAR = N_YEAR + 1

      Y(2, 1) = 6.23d0*0.40d0

      YY(2, 2, 1) = Y(2, 1)

      NPR(2, 1) = 2


          NLINE = NLINE + 1

      SUM(2) = YY(2, 2, 1) + YY(1, 1, 1) + NLINE*2.08


          N_YEAR = 1992


          I1  =  1
          I2  =  1
          NLINE = NLINE + 1


    SLP(1,1) = 2.08
      SLP(2,1) = 2.08*0.40

    SLOPE(1,1,1) = 2.08
      SLOPE(2,2,1) = 2.08*0.40

       DO  210   J = 3, JYEAR

           SUM1 = 0.0
           SUM2 = 0.0

           NYEAR  = N_YEAR + 1
           N_YEAR = N_YEAR + 1

           DO   220  I = 1, I1

                Y(J, I) = Y(J-2, I) * 0.55D0

                NPR(J, I) = NPR(J-2, I) + 1

                YY(NPR(J, I), J, I) = Y(J, I)


          SLP(J,I) = SLP(J-2,I)*0.55D0

                SLOPE(NPR(J, I), J, I) = SLP(J,I)


            SUM1 = SUM1 + YY(NPR(J, I), J, I)

220         CONTINUE
```

```
                K = I1

                DO  230  I = 1, I2

                    Y(J, K+I) = Y(J-1, I) * 0.40D0

                    NPR(J, K+I) = NPR(J-1, I) + 1

                    YY(NPR(J, K+I), J, K+I) = Y(J, K+I)

        SLP(J,K+I) = SLP(J-1,I)*0.40D0

                    SLOPE(NPR(J, K+I), J, K+I)= SLP(J,K+I)

           SUM2 = SUM2 + YY(NPR(J, K+I), J, K+I)

230     CONTINUE

          SUM(J) = SUM1 + SUM2 + SUM(J-1) + NLINE*2.08

                        NLINE = NLINE + I1 + I2
                        K1 = I2
                        K2 = I2 + I1
                        I2 = K2
                        I1 = K1

210       CONTINUE



           ICOUNT = 0

        DO 300       J   = 1, JYEAR
        DO 301       I   = 1, IPROC
        DO 302       NP = 1, NPRO

          IF(YY(NP, J, I).GT.0.0) THEN

                  ICOUNT = ICOUNT + 1

          DO  303   JJ = J+1, JYEAR


           IF(NP.EQ.1) THEN

                  EX_Y(NP,JJ,ICOUNT) = YY(NP,J,I) + (JJ-J)*2.081D0
           ELSE
            EX_Y(NP,JJ,ICOUNT) = YY(NP,J,I) + (JJ-J)*SLOPE(NP,J,I)
               ENDIF

303       CONTINUE

        END IF


302       CONTINUE
301       CONTINUE
300       CONTINUE
```

```
C       /////// PART 3: OUTPUT DATA STORING AND RESULTS  //////////

            N_YEAR = 1990

         DO 400  JJ   = 1, JYEAR

            NYEAR = N_YEAR + 1

         WRITE(6,*) '================================================'
         WRITE(6,*)  '    Year   ',N_YEAR,'-', NYEAR, ': '
         WRITE(6,*) '------------------------------------------------'

            Y_SUM(JJ) = 0.0

           DO 401  NP = 1, NPRO

            P_SUM(JJ,NP) = 0.0

           DO 402  I = 1, IPROC

       P_SUM(JJ,NP) = P_SUM(JJ,NP) + YY(NP,JJ,I) + EX_Y(NP,JJ,I)


403        CONTINUE
402        CONTINUE


           IF(P_SUM(JJ,NP).GT.0.0) THEN
           WRITE(6,*)'P_SUM(YR',JJ-1,',  NP',NP-1,') = ',P_SUM(JJ,NP)
           END IF

         Y_SUM(JJ) = Y_SUM(JJ) + P_SUM(JJ,NP)

401        CONTINUE

         WRITE(6,*) '------------------------------------------------'
         WRITE(6,*) 'Y_SUM(YR',JJ-1,') = ',Y_SUM(JJ)
         WRITE(6,*) '------------------------------------------------'
         WRITE(6,*) '          '
         WRITE(6,*) '          '
         WRITE(6,*) '          '
         WRITE(6,*) '          '

            N_YEAR = N_YEAR + 1

400        CONTINUE

         STOP
         END
```

APPENDIX 6.2

PROGRAMMING MATHEMATICAL MODELS USING EXCEL SPREADSHEET

Sheet 6.2.1: Amount of Plastics Waste Recovered in Bangladesh in Different Year by Their Process Number [Faster Recovery Scenario where time stem is 1 year].

1	B	C	D	E	F	G	H	I	J	K	L	M	N
2			Recovery Rates				Time Step						
3			40% recovery	55% recovery			(In Year)						
4			0.40	0.55			1						
5													
6		Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
7	Process Number		1st Imports										
8	Pro 0		6.23	8.31	10.39	12.47	14.55	16.63	18.71	20.79	22.87	24.95	27.03
9	Pro 1			2.49	6.75	8.73	10.70	12.68	14.65	16.63	18.61	20.58	22.56
10	Pro 2				1.00	4.07	7.20	9.08	10.96	12.83	14.71	16.59	18.47
11	Pro 3					0.40	2.18	5.12	7.59	9.38	11.16	12.94	14.73
12	Pro 4						0.16	1.09	3.25	5.85	7.93	9.62	11.32
13	Pro 5							0.06	0.52	1.90	4.13	6.39	8.21
14	Pro 6								0.03	0.24	1.05	2.69	4.83
15	Pro 7									0.01	0.11	0.55	1.65
16	Pro 8										0.00	0.05	0.28
17	Pro 9											0.00	0.02
18	Pro 10												0.00
19	Total amount		6.23	10.80	18.14	25.67	34.79	44.66	55.71	67.64	80.57	94.38	109.09

Sheet 6.2.2: Spreadsheet Model for Determining the Amount of Plastics Waste Recovered in Bangladesh in Different Year by Their Process Number [Faster Recovery Scenario] as is shown in Table 6.2.1.

1	B	C	D	E	F	G	H	I
2			Recovery Rates				Time Step	
3			40% recovery	55% recovery			(In Year)	
4			0.40	0.55			1	
5								
6		Year	1990	1991	1992	1993	1994	1995
7	Process Number		1st Imports					
8	Pro 0		6.23	=2.08*H4+D8	=2.08*H4+E8	=2.08*H4+F8	=2.08*H4+G8	=2.08*H4+H8
9	Pro 1			=D8*D4+C8*E4	=E8*D4+D8*E4	=F8*D4+E8*E4	=G8*D4+F8*E4	=H8*D4+G8*E4
10	Pro 2				=E9*D4+D9*E4	=F9*D4+E9*E4	=G9*D4+F9*E4	=H9*D4+G9*E4
11	Pro 3					=F10*D4+E10*E4	=G10*D4+F10*E4	=H10*D4+G10*E4
12	Pro 4						=G11*D4+F11*E4	=H11*D4+G11*E4
13	Pro 5							=H12*D4+G12*E4
14	Pro 6							
15	Pro 7							
16	Pro 8							
17	Pro 9							
18	Pro 10							
19	Total amount		=SUM(D8:D18)	=SUM(E8:E18)	=SUM(F8:F18)	=SUM(G8:G18)	=SUM(H8:H18)	=SUM(I8:I18)

Continued ..... Sheet 6.2.2:

1	B	J	K	L	M	N
2						
3						
4						
5						
6		1996	1997	1998	1999	2000
7	Process Number					
8	Pro 0	=2.08*H4+I8	=2.08*H4+J8	=2.08*H4+K8	=2.08*H4+L8	=2.08*H4+M8
9	Pro 1	=I8*D4+H8*E4	=J8*D4+I8*E4	=K8*D4+J8*E4	=L8*D4+K8*E4	=M8*D4+L8*E4
10	Pro 2	=I9*D4+H9*E4	=J9*D4+I9*E4	=K9*D4+J9*E4	=L9*D4+K9*E4	=M9*D4+L9*E4
11	Pro 3	=I10*D4+H10*E4	=J10*D4+I10*E4	=K10*D4+J10*E4	=L10*D4+K10*E4	=M10*D4+L10*E4
12	Pro 4	=I11*D4+H11*E4	=J11*D4+I11*E4	=K11*D4+J11*E4	=L11*D4+K11*E4	=M11*D4+L11*E4
13	Pro 5	=I12*D4+H12*E4	=J12*D4+I12*E4	=K12*D4+J12*E4	=L12*D4+K12*E4	=M12*D4+L12*E4
14	Pro 6	=I13*D4+H13*E4	=J13*D4+I13*E4	=K13*D4+J13*E4	=L13*D4+K13*E4	=M13*D4+L13*E4
15	Pro 7		=J14*D4+I14*E4	=K14*D4+J14*E4	=L14*D4+K14*E4	=M14*D4+L14*E4
16	Pro 8			=K15*D4+J15*E4	=L15*D4+K15*E4	=M15*D4+L15*E4
17	Pro 9				=L16*D4+K16*E4	=M16*D4+L16*E4
18	Pro 10					=M17*D4+L17*E4
19	Total amount	=SUM(J8:J18)	=SUM(K8:K18)	=SUM(L8:L18)	=SUM(M8:M18)	=SUM(N8:N18)

==== 0O0 ====