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CHARACTERISTIC CHANGES IN RECYCLED HDPE
FROM MILK BOTTLES

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CHATE PATTANAKUL

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of the requirements for

M.S. degree in Packaging

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Major professor

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# CHARACTERISTIC CHANGES IN RECYCLED HDPE FROM MILK BOTTLES

By

Chate Pattanakul

A THESIS

Summited to
Michigan State University
in partial fulfillment of the requirements
for the degree of

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# ABSTRACT

## CHARACTERISTIC CHANGES IN RECYCLED HDPE FROM MILK BOTTLES

By

Chate Pattanakul

Recycling plastic material is a part of the solution to solid waste management problems. High density polyethylene (HDPE) milk bottles are the largest single use of HDPE bottles. To provide a basis for recycling milk bottles, the mechanical and physical changes during recycling were studied. ASTM 1238 was followed for Melt Flow Index evaluation, ASTM 638 was followed for Tensile properties test, and ASTM 256-81 was followed for Izod impact test.

Materials are recycled milk bottles blended with virgin HDPE resin by weight percent of 0, 10, 20, 50, 80, and 100% recycled material.

The most sensitive properties that show significant changes are elongation at break and Izod impact strength. Elongation at break has a range of 74% to 31% and Izod impact strength has a range of 2.522 to 2.201 ftlb/in from 100% virgin to 100% recycled materials. Other properties that did not significantly change are tensile strength, modulus of elasticity, and elongation at yield with averages of 4,900 psi, 93,000 psi, and 17% respectively.

To my father and mother, Rengyos and Suganya Pattanakul

# ACKNOWLEDGMENTS

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Finally, I am grateful to everyone who has assisted me in this work.

C. Pattanakul
6-18-1987

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# I. INTRODUCTION

The objective of this research is to evaluate the properties of recycled HDPE post-consumer milk bottles and to use this information as a guideline for potential uses as recycled materials or in blends with virgin resins.

Decisive management of consumer solid waste at the present time is very crucial. The appropriate solutions need to be found, because plastic materials are increasing in volume in solid waste every year. Recycling is the best option from the viewpoint of conservation of resources and will reduce the volume of consumer waste that will be landfilled.

There are two preconditions that must be satisfied before there can be a viable solution to the reprocessing of plastics from collected waste systems. These are : (1) a steady flow of plastic waste must be available which is not grossly contaminated by other materials which interfere with the reprocessing operation, (2) a steady market for recycled products must exist or be developed (Scott, 1976).

The first condition should be a plastic material that is widely used and easy to separate from other plastic materials. This brings our attention to HDPE milk bottles. In 1986, 680 million pounds of HDPE were used in the production of blow-molded milk bottles, along with another 1.18 billion pounds of other HDPE blow-molded bottles

(Selke, et al., 1987).

The potential uses for recycled HDPE are identified as any product that is non-food contact and has a relatively large cross-section. Any residue or contamination could leach out from a package to food and pose a risk to consumer health. A large cross-section will provide adequate strength for a product even when the material contains small amounts of contamination.

The properties of recycled HDPE and blends with virgin HDPE that have been investigated in this research were mechanical and physical properties. The mechanical properties are tensile strength, elongation at yield, elongation at complete break, modulus of elasticity and Izod impact strength. For physical properties, the melt flow index (MFI) was determined and used as an indicator for changes in molecular weight distribution in recycled HDPE compared with virgin resins.

# II. BACKGROUND AND LITERATURE REVIEW

## A. GENERAL INFORMATION ABOUT POLYMERS

To understand the behavior of recycled HDPE, we should define some principles that cause recycled materials to change their characteristics and some phenomena that we use to identify the mechanical properties of polymers.

### 1. Polymer Degradation

Definition: It is the changes in physical properties caused by chemical reactions involving bond scission in the backbone of the macromolecule (Schnabel, 1981), which lead to a reduction in molecular weight.

### 2. Modes of Polymer degradation

The initiation of polymer degradation can be caused by thermal, mechanical, photochemical, radiation, biological and chemical degradation of polymeric materials.

Chemical degradation is induced under the influence of chemicals brought into contact with polymers , usually at elevated temperatures because the activation energy for these processes is high.

Thermal degradation is when, at elevated temperatures, the polymer starts to undergo chemical changes without the simultaneous involvement of another compound.

Biological degradation is strongly related to chemical degradation. Microorganisms produce enzymes which are capable of reacting with natural and synthetic polymers. The enzymatic attack is a chemical process.

Mechanical degradation is caused by the influence of shear forces. The stress-induced processes in polymeric materials are frequently accompanied by bond ruptures in the polymer main-chains.

Light-induced polymer degradation, or photodegradation, concerns the physical and chemical changes caused by irradiation of polymers with ultraviolet or visible light. In order to be effective, light must be absorbed by the substrate. Thus, the existence of light absorbing groups in the macromolecules (or in the additives) is a prerequisite for the initiation of photochemical reactions.

High energy radiation such as electromagnetic radiation or particle radiation is not specific with respect to absorption. All parts of the molecule are capable of interacting with the radiation. The extent and character of chemical and physical changes depend on the chemical composition of the irradiated material and on the nature of the radiation.

There are strong relationships among the various types of degradation. For example, the oxidative deterioration of thermoplastic polymers during processing is based on the action of heat, mechanical forces and oxygen.

## 3. Mechanistic Aspects of Polymer Degradation Reactions

### a. Single Step Processes and Chain Reactions

In single step reactions, the reaction rate is directly proportional to the rate of initiation. Typical examples are photochemical reactions where one main-chain bond is ruptured per absorbed photon. Another example is an amylase interaction with amylose in which one glucoside bond is broken per attack.

A chain reaction is self-propagation of the process. The initiation reaction yields products that are themselves capable of undergoing spontaneous reactions with intact molecules. Under continuous initiation, the reaction rate is accelerated (Schnabel, 1981).

### b. Autooxidation

This is the reaction between oxygen and free radicals which are generated in initiation reactions.

R. : high or low molecular weight free radical, generated by decomposition of the polymer or an additive

PH : macromolecule

R. + PH ⟶ RH + P. initiation
P. + O-O ⟶ P-O-O.
P-O-O. + PH ⟶ P-O-O-H + P. propagation
P. + P. ⟶ products
R. + P. ⟶ products

R. + P-O-O. → products termination

P. + P-O-O. → products

2P-O-O. → 2P-O. + O-O

---

### c. Random and Specific Site Attack

Naturally, specific site attack is expected if macromolecules which posses only a single or a few functional groups are brought in contact with a reagent capable of reacting only with these functional groups.

Non-random main-chain scission has been observed with linear homopolymers subjected to mechanical forces: the center portions of the polymer chains are much more likely to undergo main-chain scissions than other parts of the macromolecules.

Probably the most intriguing problems concerning non-random degradation processes refer to so-called "weak links", which are mostly identical with impurities, incorporated chemically in macromolecules.

The polymers that are more likely to exhibit random degradation will be linear homopolymers (Schnabel, 1981).

## 4. Fracture Phenomena

One of the most remarkable features of the fracture or rupture of polymers is the great variety of ways in which different materials respond to stress. The elongation at break varies from less than 1% to several thousand percent ; breaking stresses vary from less than $10^8$

dyne/$cm^2$ to $2 \times 10^{10}$ dyne/$cm^2$ ; cracks may travel catastrophically at near sonic velocities, or so slowly that little change can be observed in a day ; the depth of residual deformation may be measured in centimeters or in microns.

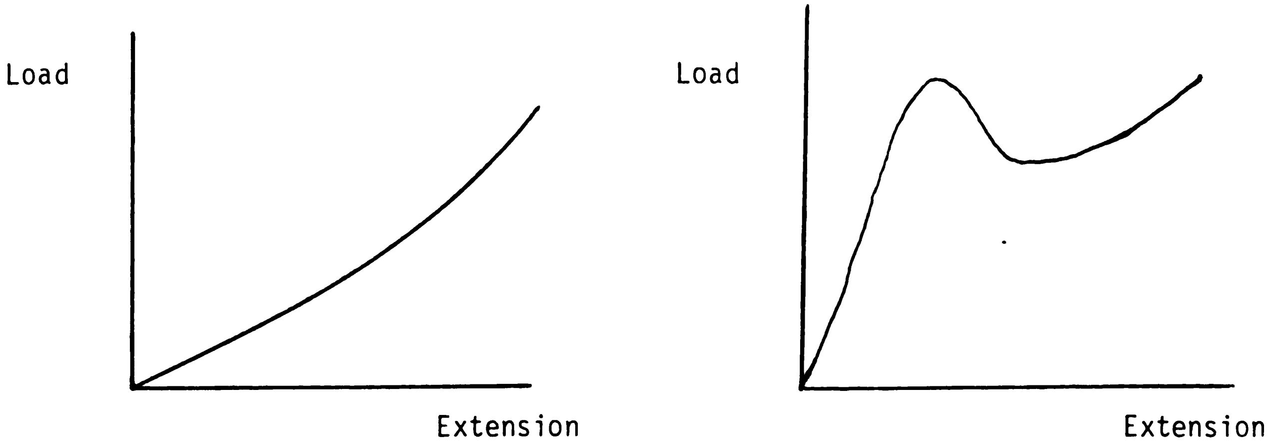
To classify different type of fracture one can use the shape of a load-deformation curve as the primary basis and supplement it by observations of deformed and broken specimens. There are 5 distinctive types of behavior for fracture: uniform extension, cold drawing, necking rupture, brittle fracture and necking rupture of the second kind (see Figure 1).

In a tensile test it is necessary to choose the shape of the specimen. Different specimen profiles will lead to different results and can not be compared with one another.

The specimen profile specified in ASTM D 638 often suffers from slippage and fracture near the clamps.

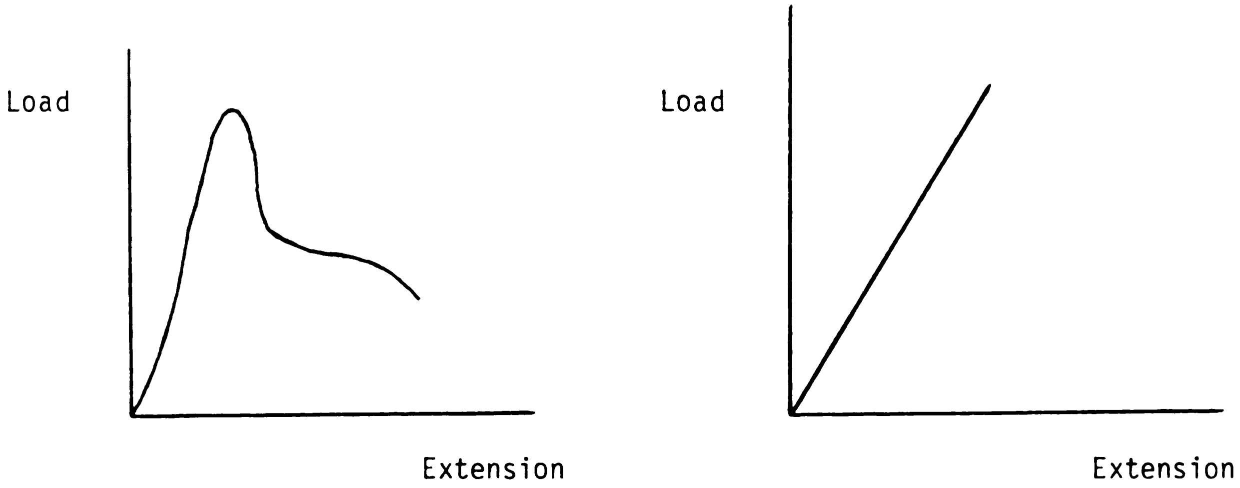
As the specimen is extended in simple tension, the molecules become oriented toward the direction of the applied force. This molecular orientation makes the specimen harder and more difficult to extend, "orientation hardening."

When a specimen deforms by cold drawing, the load-extension curve does not immediately represent the general behavior of the material but only the behavior of a specimen of a particular shape. For example, if a 10 cm long test specimen has been extended a further 10 cm, this



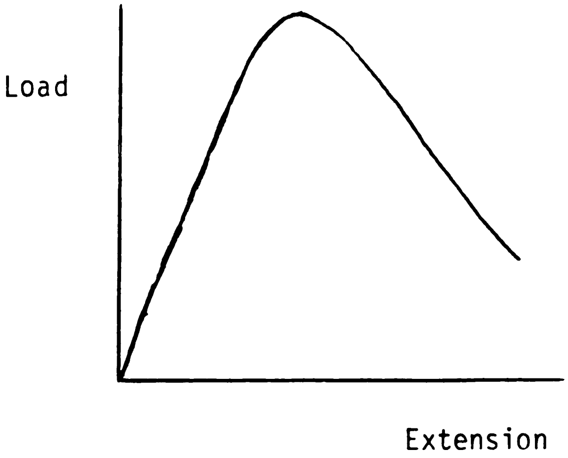
(a) Uniform extension

(b) Cold drawing



(c) Necking rupture

(d) Brittle fracture



(e) Necking rupture of the second kind

Figure 1 : Fracture behavior of polymers (Bikales, 1971)

does not mean that the strain is 100% ; some of the specimen may be strained, for example, 400% and other parts less than 10%.

Necking rupture is behavior in which the specimen necks and then breaks without restabilization of the neck.

Specimens which fail by necking rupture whiten in the neck. This is usually attributed to the occurrence of very small voids; the scattering of light at the microvoids is the cause of the white appearance. It is not ordinarily easy to demonstrate the existence of these microvoids in a photomicrograph because they are below the limit of resolution. The neck never restabilizes because the specimen breaks before the orientation hardening is sufficient. Necking shows an angle neck because yielding and necking are shear phenomena (Bikales, 1971).

### 5. Impact Resistance

Impact resistance is a property of considerable importance where the use of plastic is concerned. The ability of a fabricated article to withstand shocks is often a decisive factor in replacement of a conventional material by a polymer.

The impact resistance of a plastic article depends not only on the basic impact properties of the polymer but also on the following factors: 1) design of the object, 2) conditions during fabrication, 3) the nature of the blow, 4) environmental conditions, and 5) the frequency of the shock.

Normally, thick sections produce areas of potential weakness in that the impact resistance is less than in thinner sections. This factor is of considerable importance in the design of blow-molded containers. It is essential to avoid drastic changes of thickness and complex detail in the object.

The conditions of fabrication are more frequently responsible than any other factor for impact failure. The impact strength of polyethylene increases as the rate of cooling from melt increases and the size of the spherulites decreases. The impact strength undergoes no change once the polymer has completely solidified.

The type of molding affects the impact strength. For example, in compression-molded SBR-modified PS, the stress builds up to a level at which catastrophic failure occurs and the material undergoes a brittle fracture. In an injection-molded sample, failure at the critical stress takes place with a much slower crack propagation and a certain amount of elongation takes place. The injection-molded sample, as a result of this difference in impact behavior, has an impact strength greater than that of the compression-molded material by a factor of at least 2.

Factors that can contribute errors to the Izod Impact test are: a) variation of clamping pressure, b) failure to strike the specimens squarely, c) the state of the cutter and the cutting technique for machining notches.

## B. EFFECTS OF REPROCESSING

One of the factors that needs to be considered before making a decision to use recycled HDPE is how much change in the properties of the material will occur due to polymer degradation caused by container fabrication, grinding and contamination from the use cycle.

Much research has been done to predict the performance of various kind of recycled plastics. Some properties are severely damaged and some properties only slightly changed. Each polymer has its own characteristic changes which depend on the nature of the particular polymer.

Polymer degradation is the reaction that causes the reduction in polymer stability. Molecular weight and molecular weight distribution of the polymer have been changed. The question is how much it changes and how we can control it and what kind of detection can be done or will be the most sensitive measurement for each polymer.

Schnabel (1981) concluded that there were 6 types of initiation of polymer degradation : thermal, mechanical, chemical, biological, radiation and photooxidation degradations, which were discussed in the preceding section.

Rideal and Padget (1976) stated that there was change in the molecular structure of HDPE during processing. They found that high melt temperature (more than 290 C) would result in decreasing melt viscosity and a narrowing of molecular weight distribution, while lower melt temperature resulted in an increase in melt viscosity. The increase in melt viscosity arose from a molecular enlargement reaction which was mainly attributable to the formation of long chain branches. The decrease in melt viscosity and narrowing of MWD were caused by scission of polymer backbone. The scission and enlargement reaction are not mutually exclusive, but competitive to each other.

During processing the shear degradation result was consistent with the theory that in a viscous matrix the action of high shear forces preferentially cuts a polymer chain at the center leading to a narrowing of MWD.

Abbas (1980) studied the degradation of polycarbonate during recycling in a capillary rheometer. He found that at high constant shear stresses (0.15-0.95 MPa) and at temperatures between 275° and 320° C the degradation kinetics were non-random chain scission. He concluded that bonds were more susceptible to scission the closer they were to the middle of the polymer molecule, and that the extent of degradation increased with an increase in molecular weight.

Mellor et al (1973) stated that the lifetime of polyolefins in the presence of UV light was dependent on the degree of oxidation occurring during the prior processing operation.

Luongo (1963) found that the rate of oxygen uptake in solid PE during oxidation was inversely proportional to the percent crystallinity. Only the amorphous regions of semicrystalline polyethylene were sensitive to oxygen attack. He used two polyethylene samples: one was highly crystalline polyethylene of density 0.96 and the other a branched polyethylene of density 0.92. The samples were oxidized by exposing them to oxygen at 100 C under controlled conditions over a period of 400 hours, and were examined at intervals by infrared spectroscopy.

Sadrmohaghegh and Scott (1980) studied the effects of reprocessing on low density polyethylene. The results of their experiment showed an increase in melt viscosity, rapid formation of gel, increase in tensile strength and elongation at break during the first 10 minutes of processing and then the beginning of a decline after 20 minutes of processing. They explained that allylic radicals were formed in the polymer by mechanochemical and oxidative reactions during processing that led to cross-linking and then later to chain-scission following thermolysis of the hydroperoxide.

Mitterhofer (1980) stated that chain scission and cross linking occurred simultaneously during the processing of HDPE. Depending upon conditions of temperature, oxygen availability and polymer type, any one might prevail over the other. The cross-linking of an HDPE was detected by a drastic drop in the melt flow index after 10 minutes of residence time in the melt index apparatus.

Scott (1976) suggested that stringent precautions needed to be taken to eliminate the effects of oxygen during the reprocessing operation, otherwise the reprocessed product would be different both chemically and mechanically from that made from virgin material. For consumer waste plastic, the environmental exposure caused further rapid changes in the composition of the polymer which greatly affected its behavior on reprocessing and presented a technical problem in polymer stabilization. Consumer waste plastic, unless effectively cleaned, will contain small amounts of metal ions which are both thermal and UV pro-oxidants. The effect of light on thermally processed polymer is the introduction of unsaturated groups which themselves act as pro-oxidants in a reprocessing operation. In order to control degradation in reprocessed polymers, he suggested using more effective antioxidants which prevent the initiation process, such as metal deactivators, UV absorbers and peroxide decomposers.

## C. RESEARCH ON PROPERTIES OF POLYMER MATERIALS

Properties of polymers are affected by polymer structure. In the same kind of polymer, Molecular Weight (MW) and Molecular Weight Distribution (MWD) will play important roles in the performance of the material. The physical and mechanical characteristics of recycled polymers such as flow behavior, tensile strength, elongation and impact strength are different from and generally inferior to those of virgin polymer.

For recycled material it was expected that there would be a reduction in molecular weight and narrowing of MWD caused by polymer degradation. Much research confirming this has been done on various polymer materials (Bevis et al. 1975, Scott 1976, Stamper and Connole 1984, Sayago and Petrie 1985).

Perron and Lederman (1972) worked on polyethylene films that had different MWDs. They found that impact strength increased as the MWD was broadened. They explained this behavior by molecular entanglement theory. Broader MWD meant more of the high MW portion that would increase molecular entanglement.

Bikales (1971) concluded that as the average MW decreased, there was a tendency for breaking stresses, strains and energies to decrease, but for little or no change in moduli and yield stresses. For HDPE, the material showed more ductility under stress as the MW decreased.

Shenoy et al.(1983) proposed the use of MFI information as an indicator of the effect of processing history and suitable end use for a particular polymer material. The MFI value also indicates the average MW of the polymer.

Blends of recycled and virgin material cause a reduction in mechanical properties. Normally, a maximum of 20% in-plant recycled materials was used to mix with virgin resin for production without significant differences in product quality (Abbas et al., 1978).

## III. MATERIALS AND METHODS

### A. Material Preparation

Collected milk bottles were rinsed with cold water, then dried at room temperature. A lowline granulator model 68-913 from Polymer Machinery Corp. was used to chop the milk bottles into a flaked form. Next contaminants (milk, dirt etc.) were separated by passing the recycled material into an agitated cold water tank, overflowing through a screen, and then leaving them to dry at room temperature. The blends of virgin and recycled HDPE, in weight percent, were physically mixed by a propeller feed mixer for 30 minutes.

### B. Melt Flow Index Determination

Materials and Apparatus:

-Virgin HDPE "FORTIFLEX A60-70-119" from Soltex Polymer Corp.

-Recycled HDPE milk bottles separated by brand

-Regrind unused HDPE bottles from Heatherwood Farms Dairy that were made from pure virgin material which came from the same lot of virgin HDPE stock.

-Recycled used HDPE milk bottles from Heatherwood Farms Dairy that came from the same lot as the unused bottles. (Milk bottles in half gallon size from the same lot as the unused bottles, filled by Heatherwood Farms Dairy, were purchased at a local food store. These samples were stored under refrigeration until the expiration date, then were cleaned and chopped into flake form.)

-Recycled used HDPE milk bottles mixed from different sources.

-Melt Flow Indexer, Ray-Ran model 2A Digital Auto

Procedure:

ASTM standard 1238 was followed. The Melt Flow Indexer temperature control was set at 190° +/- 0.2° C with die and piston in the cylinder. Warm up usually took about 30 minutes to get a constant temperature. Sample resin (3-3.5 gm) was put in the cylinder with the charging tool. The sample was preheated for 6 minutes in order to allow the sample to completely melt and have a constant flow rate. The 2.16 kg dead load was used and run under the automatic mode that allows the piston to travel for 6.35 mm. The collected data were times in seconds. The MFI value was determined using the formula,

$$\text{MFI (g/10 min)} = \frac{207}{\text{time(second)}}$$

where 207 is the factor for calculating the flow rate of polyethylene from ASTM D 1238, from

$$\begin{aligned}\text{Flow rate} &= (427 \times L \times d)/t \\ &= \text{weight}/t\end{aligned}$$

where:

L = length of calibrated piston travel, cm.
d = density of resin at test temperature, $g/cm^3$
t = time of piston travel for length L, second
427 = mean of areas of piston and cylinder x 600
(600 = 60 sec/min x 10 min)

In this experiment,

L = 0.635 cm.
d = 0.7636 $g/cm^3$ (from ASTM D 1238)

C. Estimating the change in Molecular Weight Distribution from virgin HDPE to regrind HDPE by the Melt Flow Index Technique

Materials and Apparatus:

-Virgin HDPE "FORTIFLEX A60-70-119" of Soltex Polymer Corp.
-Recycled HDPE milk bottles
-Melt Flow Indexer, Ray-Ran model 2 A

Procedure:

The Melt Flow Indexer was operated at different shear rate by varying the dead load from 2.16 to 5.0, 7.5, and 10.0 kg. From the Melt Flow Index values, viscosity as a function of shear rate was obtained by,

$$\text{Shear stress} = \frac{Rn \quad F}{2 \times 3.1416 \ Rp^2 \ L}$$

$$\text{Shear rate} = \frac{4\,Q}{3.1416\,Rn^{3}}$$

From ASTM 1238 specifications for piston and die dimensions

Rn = nozzle radius 1.0475 mm.

Rp = piston radius 4.737 mm.

L = nozzle length 8.00 mm.

F = test load x 9.807 x $10^{5}$

Q = flow rate = MFI/(600 x density)

From the above information, we can simplify the formula to,

$$\text{Shear stress} = 9.11 \times 10^{4} \times W$$

where W = test load in kg.

$$\text{Shear rate} = \frac{1.84\ \text{MFI}}{\text{density}}$$

$$\text{Viscosity} = \frac{\text{shear stress}}{\text{shear rate}}$$

## D. Tensile Properties Determination

### Materials and Apparatus

-Materials were the same as Melt Flow Index determination, except recycled HDPE milk bottles separated by brand were not used.

-Carver Laboratory Press compression molding machine, model M 25 ton.

-Instron Tensile tester

-Tensilkut cutting machine.

### Procedure:

ASTM standard 638 was followed. Virgin granulated HDPE and recycled HDPE milk bottles were compression molded using a Carver Laboratory Press into 5 inches by 5 inches by 0.1 inch plastic sheets. The condition of molding was heating at 210° C for 6 minutes, then cooling to 50°C within 8 minutes. The plastic sheets were cut into 0.75 inch by 5 inch strips with a band saw, then shaped into dumbbell shape type 1 according to ASTM 638 by a Tensilkut machine. These samples were conditioned at 25°C, 50% RH for 2 days before running the tensile test.

An Instron, model no. 1114, was used. An adjustable load cell with scale capacities of 200, 500, 1000, 5000, and 10000 lbs was installed. For testing, the Instron was set at 500 lbs range, 2 in/min. cross head speed, 5 in/min chart speed. A specimen was placed between the grips with abrasive paper to prevent slippage. Five samples were tested and results from the chart recorder were analysed to calculate tensile strength, modulus of elasticity, elongation at yield and elongation at break.

Sample mixtures of virgin material and recycled material in weight percents of 10%, 20%, 50%, and 80% were prepared and tested in the same manner.

## E. Impact Strength Determination

Materials and Apparatus

-Materials are the same as for the tensile properties determination.

-Impact Tester from TMI, model 43-02, monitor/impact

-Notching machine from TMI

-Carver Laboratory Press, model M 25 ton

-Band saw

Procedure:

ASTM standard 256-81 was followed. Samples were prepared by compression molding virgin pellets, chopped recycled material, or mixtures of recycled material and virgin material in proportions of 10%, 20%, 50%, and 80% by weight of recycled materials. The molding condition was 210° C, 25000 lbs for 6 minutes, then cooling to 50° C within 8 minutes, producing a sheet 5 inches by 5 inches by 0.125 inches. The molded sheets were conditioned at 24°C for 2 days, and then cut into test samples 2.5 inches long and 0.5 inches wide. They were notched with a 0.1 inch deep cut. In the testing procedure the thickness of the original sheet is the width of the specimens. Eight samples were cut from each molded sheet. All tests were performed at 24°C.

### F. Data Analysis Procedure

The software program M-Stat written by Scott P. Eisensmith and Ken W. Rorick, Crop and Soil Science Department, Michigan State University, was used with an IBM-PC to analyse all data.

## IV. RESULTS AND DISCUSSION

### A. Melt Flow Index Value (MFI)

#### 1. Results:

The average MFIs for 3 samples of virgin HDPE were 0.578, 0.592 and 0.727 g/10 min. These average values were obtained from at least 3 replications. The recycled HDPE materials were collected from different sources over time, and were separated by brand. (Note: the term "recycled" will always mean post-consumer materials.) The MFI values ranged from 0.635 to 0.750 g/10 min. (see Table 1).

Table 2 shows the MFI for those materials received from Heatherwood Farms, a local dairy producer. The MFI of virgin resins, blown but unused bottles from pure virgin materials, and post-consumer bottles that came from the same lot as the unused bottles are 0.727, 0.753, and 0.715 g/10 min. respectively.

Table 3 shows MFI values for virgin material, recycled material, and mixtures between recycled and virgin HDPE.

#### 2. Discussion:

From the variation in the MFI value of recycled milk bottles, we can see that there is a range of flow properties in the materials that are used for producing milk bottles. This observation was confirmed by the difference in MFI for the first and second lots of virgin HDPE received from Heatherwood Farms.

The mixtures of virgin and recycled HDPE did not show any significant differences in MFI, and there was also no significant change in MFI between the blown but unused bottles and the post-consumer bottles, compared with virgin material from the same lot. This may be due to cross-linking between molecules balancing the molecular breakdown caused by mechanical and thermal degradation of the polymer by shear forces and elevated temperatures during container fabrication and grinding into flake form. As was discussed earlier, both these reactions are known to occur during processing of HDPE (Rideal and Padget 1976, Mitterhofer 1980).

MFIs of virgin resin in Table 2 and 3 were different, because they were tested at different times. The value in Table 2 was obtained about 5 months before the experiment for Table 3 was conducted. The aging of the polymer over that time period evidently resulted in a lower MFI value.

## TABLE 1

## MELT FLOW INDEX OF HDPE MILK BOTTLES IN LANSING MICHIGAN (g/10 min.)

| Material | Mean | SD. | Replication |
|---|---|---|---|
| Virgin resin (Heatherwood) | | | |
| lot 1 | 0.584 | 0.020 | 7 |
| lot 2 | 0.727 | 0.021 | 5 |
| Recycled bottles (Heatherwood) | | | |
| lot 1 | 0.726 | 0.011 | 4 |
| lot 2 | 0.695 | 0.034 | 4 |
| lot 3 | 0.635 | 0.094 | 8 |
| lot 4 | 0.731 | 0.012 | 5 |
| Recycled bottles (Meijer) | | | |
| lot 1 | 0.700 | 0.012 | 7 |
| lot 2 | 0.701 | 0.011 | 4 |
| Recycled bottles (Country Fresh) | 0.699 | 0.004 | 4 |
| Recycled bottles (Sta-Fresh) | 0.744 | 0.008 | 4 |
| Recycled bottles (Springdale) | 0.750 | 0.005 | 5 |

## TABLE 2

## EFFECTS OF CONTAINER FABRICATION & REGRINDING AND OF USE CYCLE ON MFI VALUE

| Material | Mean (g/10 min.) | SD. | Replications |
|---|---|---|---|
| Virgin Resin | 0.727 | 0.021 | 5 |
| Regrind unused bottles (in-plant) | 0.753 | 0.012 | 5 |
| Recycled post-consumer bottles | 0.715 | 0.012 | 5 |

## TABLE 3

## MFI OF MIXTURES OF VIRGIN AND RECYCLED HDPE MILK BOTTLES

| Material | Mean | SD. | Replications |
|---|---|---|---|
| Virgin resin | 0.691 | 0.008 | 5 |
| 10% Recycle | 0.686 | 0.013 | 5 |
| 20% Recycle | 0.696 | 0.011 | 5 |
| 50% Recycle | 0.685 | 0.003 | 5 |
| 80% Recycle | 0.688 | 0.014 | 5 |
| 100% Recycle | 0.681 | 0.004 | 5 |

## B. Estimation of changes in the Molecular Weight distribution

### 1. Results:

The MFI values increased as the loads increased, as expected (see Table 4). The MFI changes were from 0.260 to 12.577 g/10 min. as the loads varied from 1.1 kg to 10 kg. The viscosity of virgin and recycled HDPE varied with the shear rate by about the same magnitude (see Table 5).

### 2. Discussion:

Polyethylene is a shear sensitive material. Graessley (1984) stated that a lower molecular weight for a polymer would result in a higher MFI, and that a narrower MWD would result in lower viscosity at low shear rate (less than 0.1 sec$^{-1}$) and a higher viscosity at high shear rate (more than 1.0 sec$^{-1}$). In another words, broad MWD resins are more shear sensitive than narrow MWD resins (see Figure 2).

For this experiment, we investigated the low shear rate range (0.005 to 0.2 sec$^{-1}$). If there were changes resulting in a lower MW and narrower MWD, we expected lower viscosity at the same shear rate.

From Table 5, an increase in shear rate resulted in a decrease in the melt viscosity of HDPE, but no significant differences in molecular weight and molecular weight distribution between virgin and recycled HDPE were demonstrated, as the curves of viscosity vs. shear rate of virgin and recycled HDPE were on almost the same line (see Figure 3).

Again, the masking of chain scission by cross-linking may be occurring.

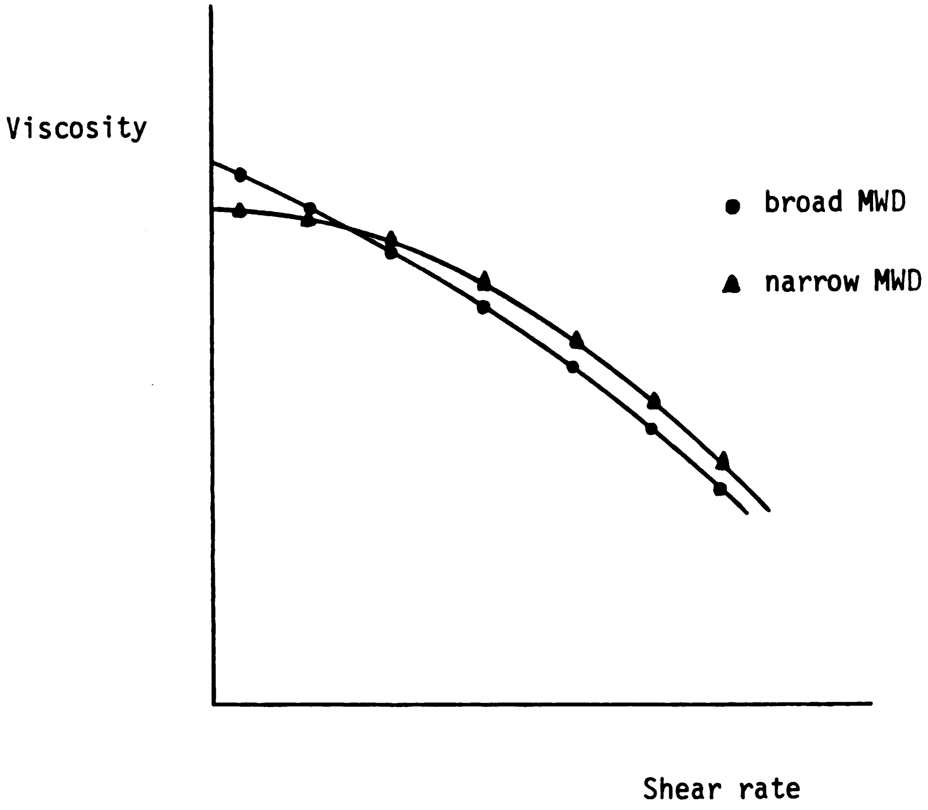


Figure 2 : The effect of MWD on viscosity & shear rate (Graessley, 1984)

# TABLE 4

## MELT FLOW INDEX vs. LOAD

| Load<br>(kg) | MFI (g/10 min.)<br>Virgin | <br>Recycle |
|---|---|---|
| 1.1 | 0.260 | 0.267 |
| 2.16 | 0.727 | 0.704 |
| 3.8 | 1.925 | 1.949 |
| 5.0 | 3.044 | 3.198 |
| 10.0 | 12.577 | 11.504 |

# TABLE 5

## EFFECTS OF SHEAR RATE ON VISCOSITY

| | Virgin | | Recycle | |
|---|---|---|---|---|
| Load (kg) | Shear rate (1/sec) | Viscosity (g/cm sec) | Shear rate (1/sec) | Viscosity (g/cm sec) |
| 1.1 | 0.0049 | 2.03 E+7 | 0.0051 | 1.969 E+7 |
| 2.16 | 0.0138 | 1.43 E+7 | 0.0134 | 1.472 E+7 |
| 3.8 | 0.0367 | 9.45 E+6 | 0.0390 | 8.9 E+6 |
| 5.0 | 0.0580 | 7.87 E+6 | 0.0610 | 7.49 E+6 |
| 10.0 | 0.2397 | 3.81 E+6 | 0.2193 | 4.163 E+6 |

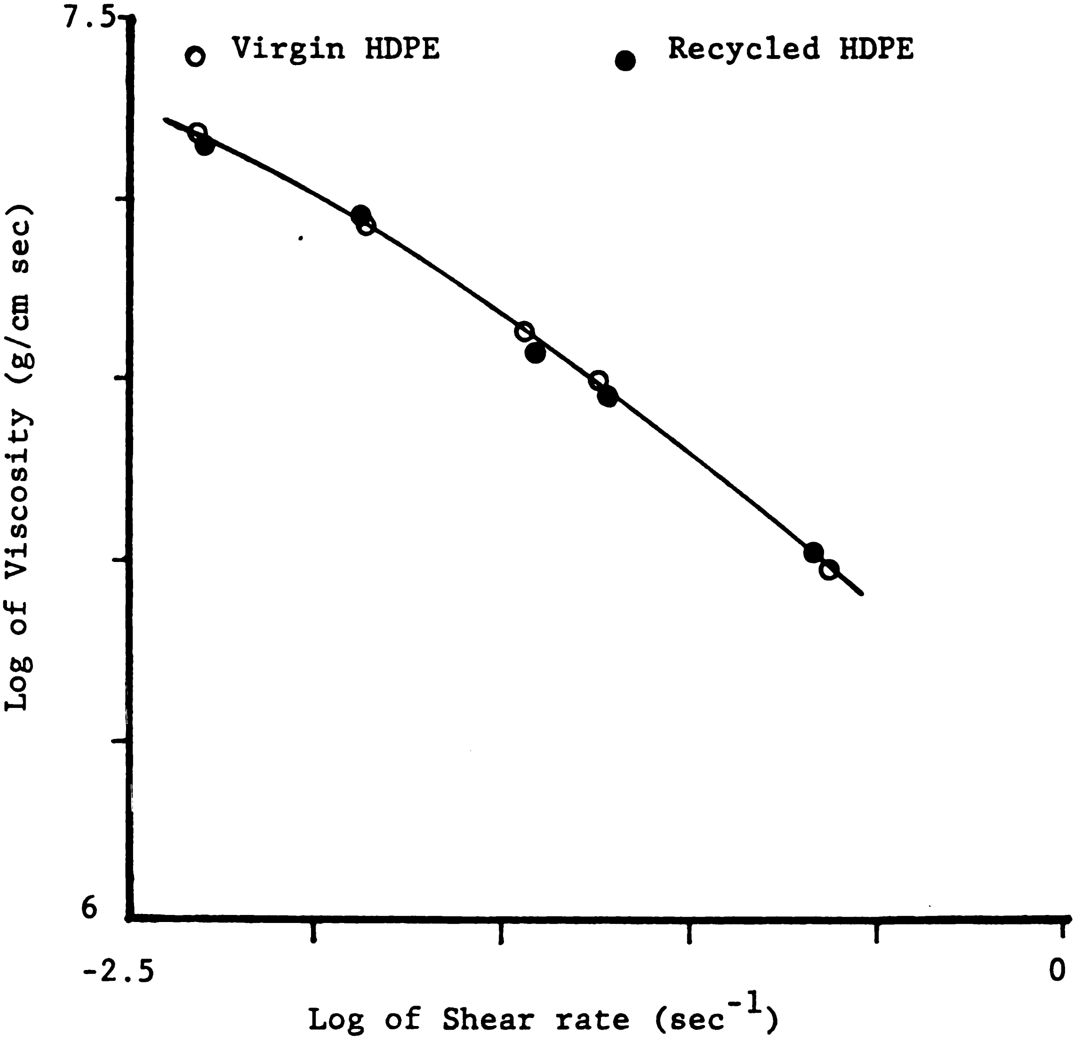


Figure 3: Estimation of changes in MWD

### C. Tensile Properties

#### 1. Results:

From Tables 6, 7, 8, and 9, we can see that the tensile strength, modulus of elasticity and elongation at yield do not significantly change from virgin material to blends to 100% recycled HDPE. Only elongation at break shows significant changes. In other words, the critical property that can be detected is elongation at complete break. The tensile strength averages about 4,900 psi. The elongation at yield averages about 17% and the modulus of elasticity averages about 93,000 psi.

#### 2. Discussion:

The assumption of polymer degradation in recycled milk bottles involving both polymer main-chain scission and cross-linking occurring at the same time can again be used to explain this behavior. These two reactions appear to balance each other, resulting in maintenance of the tensile strength, modulus of elasticity, and elongation at yield.

The elongation at break is more complex. From Appendix B, the typical graphs of the tensile tests demonstrate the differences in fracture behavior of the polymer. The 80% and 100% recycled HDPE in the mixtures with virgin resin appear to be "necking rupture of the second kind", while the 0, 10, 20, and 50% recycled HDPE in the mixtures are "necking rupture" according to the classifications discussed by Bikales (1971) and shown in Figure 1.

TABLE 6

TENSILE STRENGTH
(psi)

| Material | Run 1 | | Run 2 | |
|---|---|---|---|---|
| | Mean | SD. | Mean | SD. |
| Virgin HDPE | 4890 | 158 | 4780 | 56 |
| 10% Recycled | 4830 | 62 | 4960 | 156 |
| 20% Recycled | 4800 | 51 | 4930 | 213 |
| 50% Recycled | 4900 | 100 | 4990 | 243 |
| 80% Recycled | 4960 | 175 | 5080 | 183 |
| 100% Recycled | 4960 | 143 | 5020 | 252 |

TABLE 7

MODULUS OF ELASTICITY
(psi)

| Material | Run 1 | | Run 2 | |
|---|---|---|---|---|
| | Mean | SD. | Mean | SD. |
| Virgin HDPE | 86500 | 12800 | 83800 | 5080 |
| 10% Recycled | 87000 | 6810 | 88600 | 11700 |
| 20% Recycled | 99900 | 20300 | 84400 | 13700 |
| 50% Recycled | 97400 | 17800 | 92000 | 4550 |
| 80% Recycled | 98700 | 23800 | 102000 | 18100 |
| 100% Recycled | 92800 | 14700 | 98600 | 9910 |

## TABLE 8

### ELONGATION AT YIELD (%)

| Material | Run 1 | | Run 2 | |
|---|---|---|---|---|
| | Mean | SD. | Mean | SD. |
| Virgin HDPE | 17 | 1.22 | 17.3 | 0.98 |
| 10% Recycled | 18 | 0.93 | 17.2 | 0.67 |
| 20% Recycled | 16.4 | 1.44 | 17.6 | 0.76 |
| 50% Recycled | 17 | 1.7 | 17.4 | 0.86 |
| 80% Recycled | 17.5 | 0.79 | 17.2 | 0.66 |
| 100% Recycled | 16.2 | 1.68 | 17.4 | 0.33 |

## TABLE 9

### ELONGATION AT COMPLETE BREAK (%)

| Material | Run 1 | | Run 2 | |
|---|---|---|---|---|
| | Mean | SD. | Mean | SD. |
| Virgin HDPE | 69.7 | 16.5 | 74.0 | 17.5 |
| 10% Recycled | 62.7 | 10.1 | 62.4 | 6.54 |
| 20% Recycled | 47.2 | 8.77 | 51.3 | 12.5 |
| 50% Recycled | 48.9 | 18.7 | 41.4 | 19.4 |
| 80% Recycled | 35.1 | 9.24 | 34.6 | 9.44 |
| 100% Recycled | 36.9 | 18.2 | 30.7 | 4.74 |

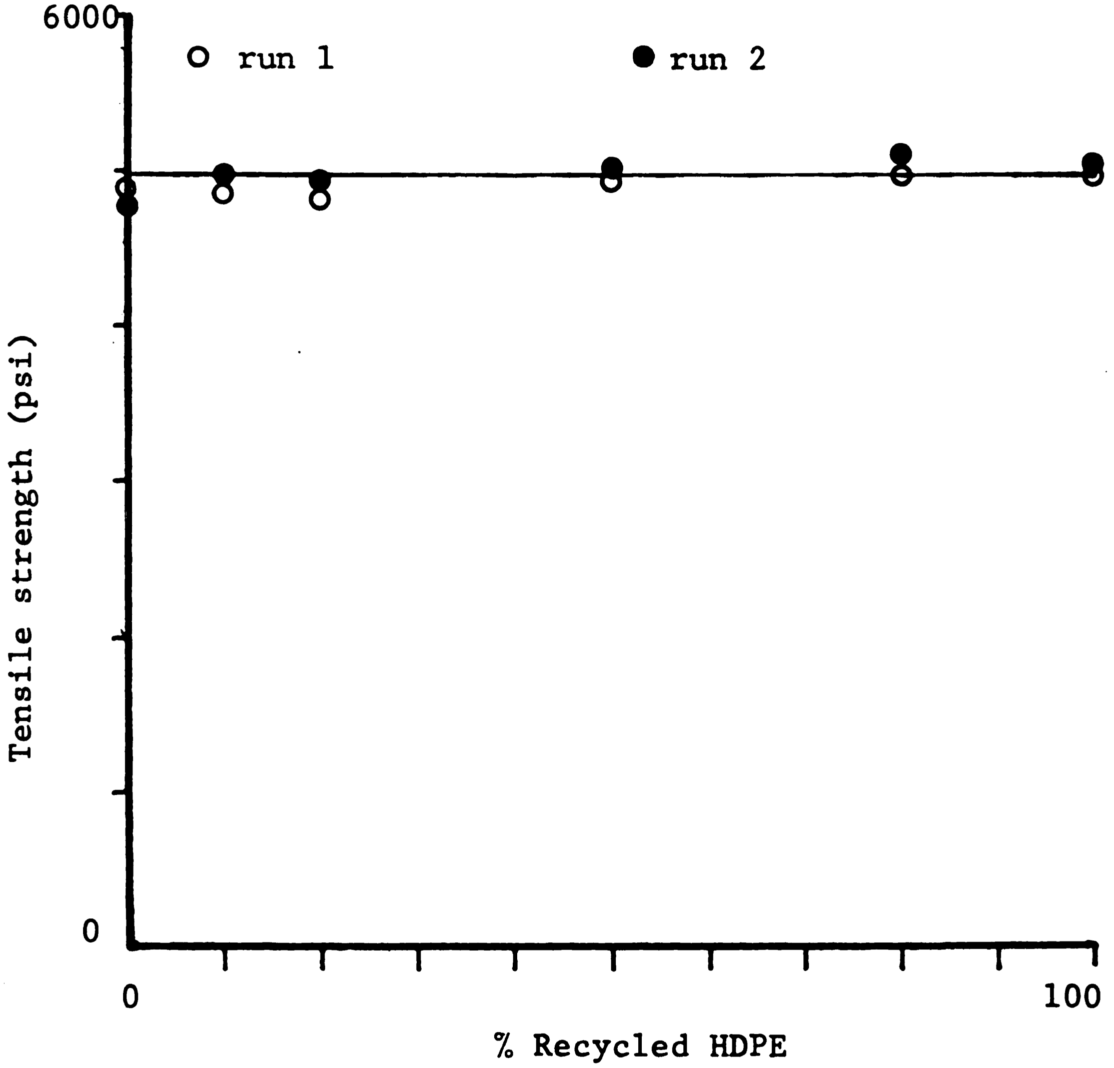


Figure 4: Tensile strength comparisons

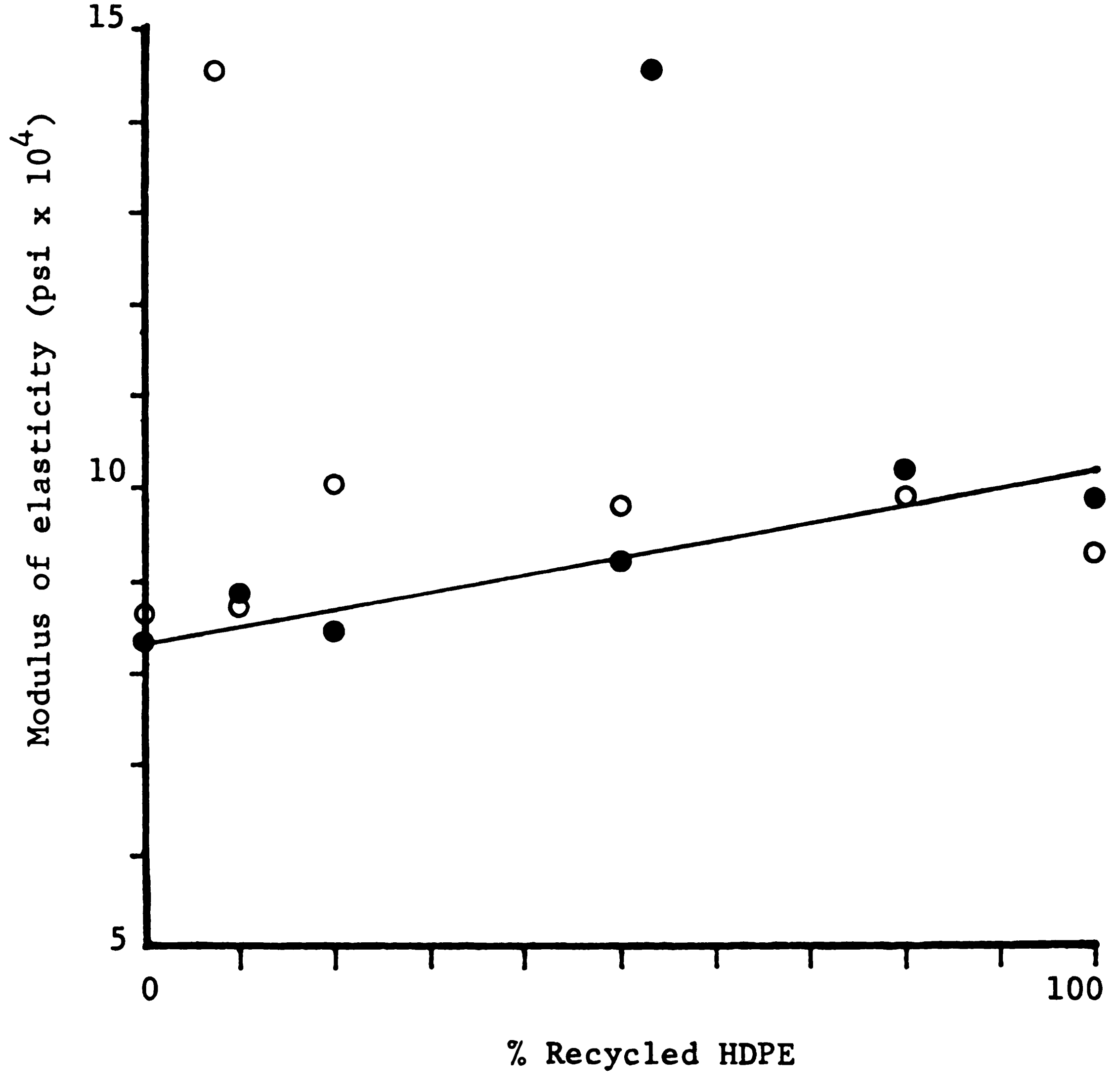


Figure 5: Modulus of elasticity comparisons

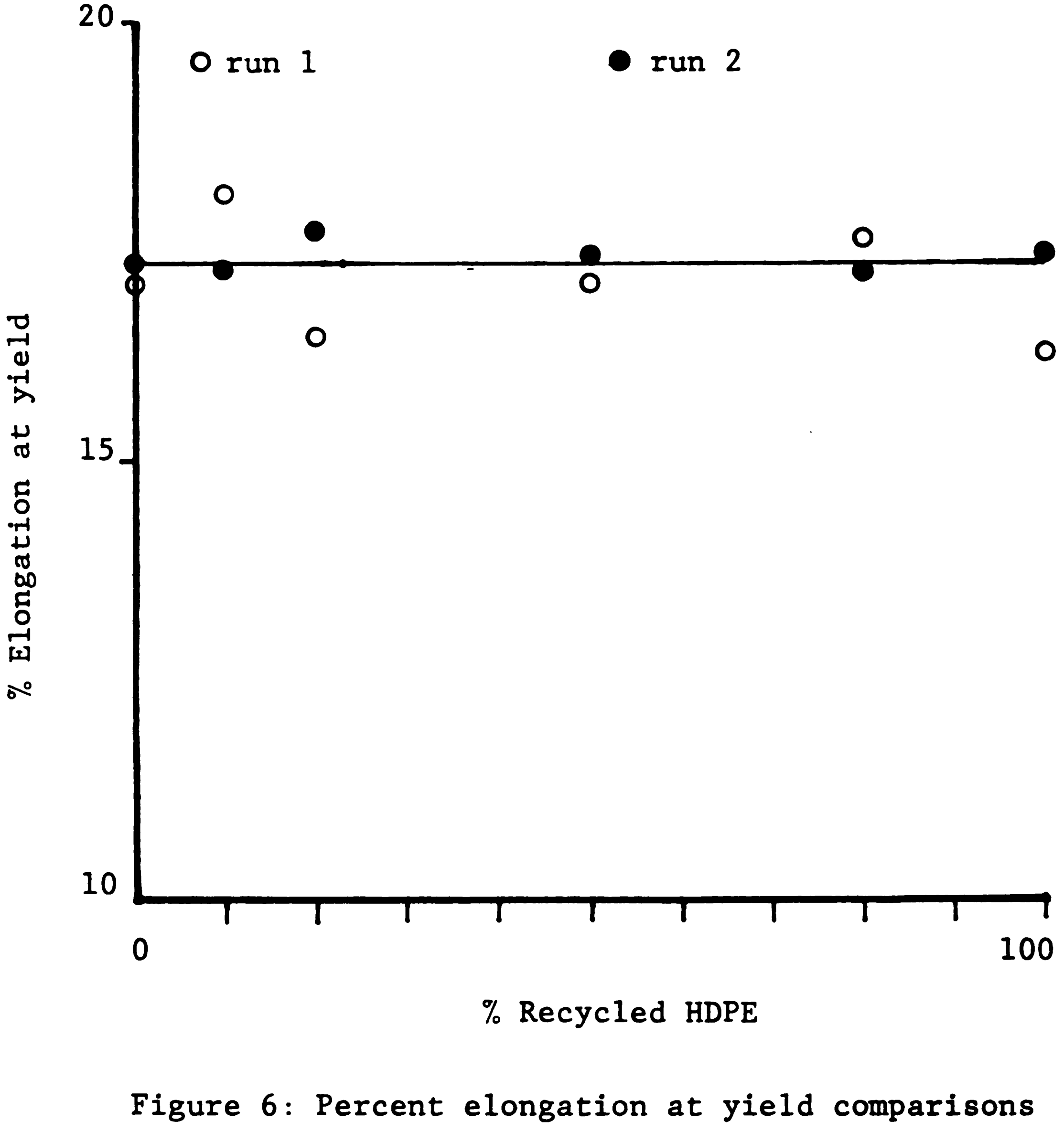


Figure 6: Percent elongation at yield comparisons

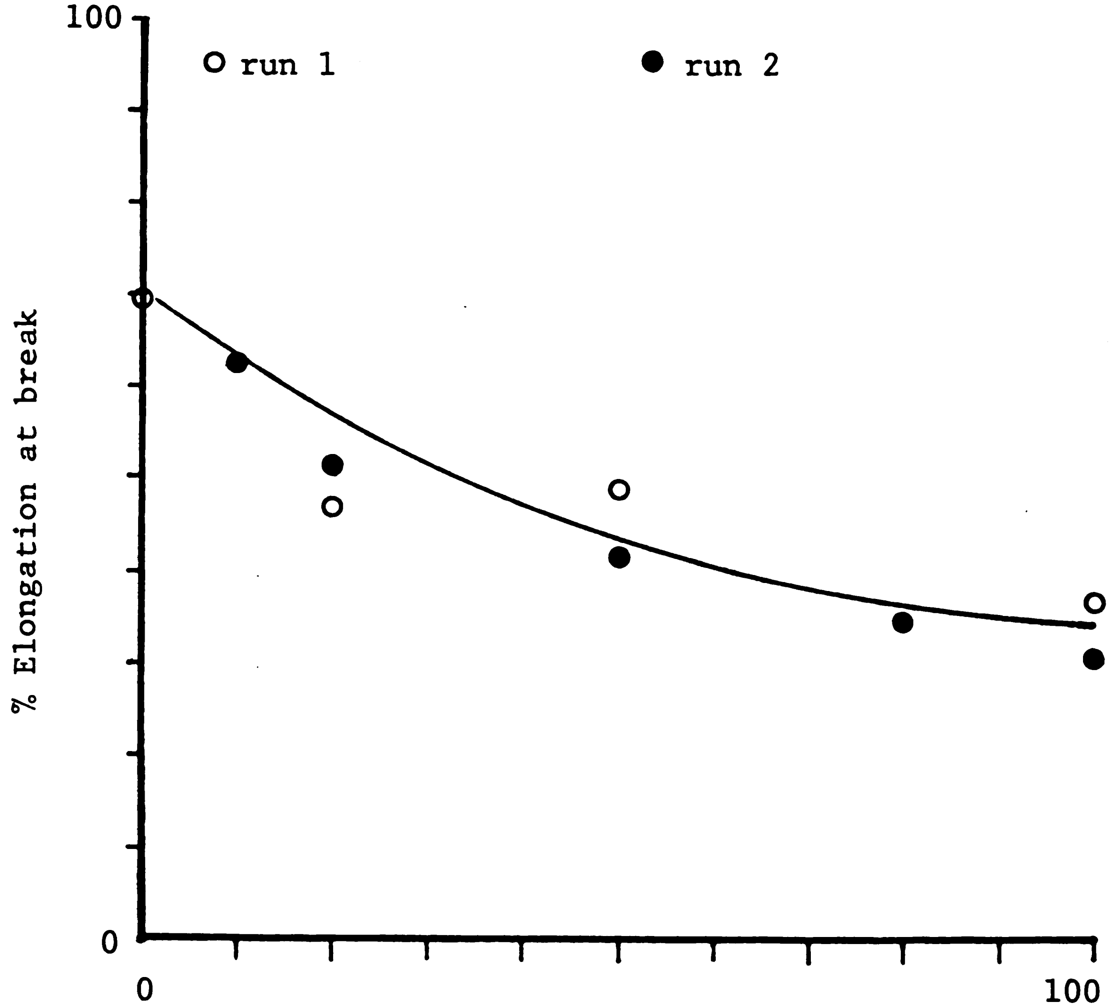


Figure 7: Percent elongation at break comparisons

## D. Impact Strength

### 1. Results:

Izod impact strength comparisons of virgin material, unused bottles and post-consumer bottles known to be from the same lot of HDPE show significant changes, as can be seen in Table 10. All failures were classified as partial break as defined in ASTM D 256. The reduction in strength compared to virgin resin is about 16% for unused bottles and about 36% for used bottles.

For recycled blends, in Table 11, the Impact strength started to drop at about 20% recycled HDPE in the blend. In this case the recycled HDPE has an impact strength about 13% lower than the virgin resin.

### 2. Discussion:

It has been demonstrated that Izod impact strength is one of the sensitive properties that can be used to detect changes in polymer materials. Several researchers did similar kinds of work and concluded that a lower molecular weight and narrower MWD resulted in decreasing impact strength. Perron and Lederman (1972) explained that the higher molecular weight material has longer chains, leading to more molecular entanglement, thus requiring higher energy to break the material. The broader MWD has more of the high molecular weight end that will dominate the resistance to impact force.

The impact strength values of virgin HDPE in Tables 10 and 11 are different due to differences in experiment time periods and variation in sample preparation.

TABLE 10

EFFECT OF USE CYCLE ON IZOD IMPACT STRENGTH

(ft lb/in)

| Material | Mean | SD. |
|---|---|---|
| Used bottles | 1.883 | 0.243 |
| | 1.720 | 0.141 |
| Unused bottles | 2.356 | 0.086 |
| | 2.364 | 0.170 |
| Virgin HDPE | 2.690 | 0.232 |
| | 2.913 | 0.260 |

TABLE 11

IZOD IMPACT STRENGTH OF MIXTURES OF VIRGIN AND RECYCLED HDPE (ft lb/in)

| Material | Mean | SD. |
|---|---|---|
| Virgin HDPE | 2.522 | 0.16 |
| 10% recycled | 2.693 | 0.261 |
| 16.7% recycled | 2.608 | 0.156 |
| 50% recycled | 2.409 | 0.138 |
| 80% recycled | 2.231 | 0.238 |
| 100% recycled | 2.201 | 0.144 |

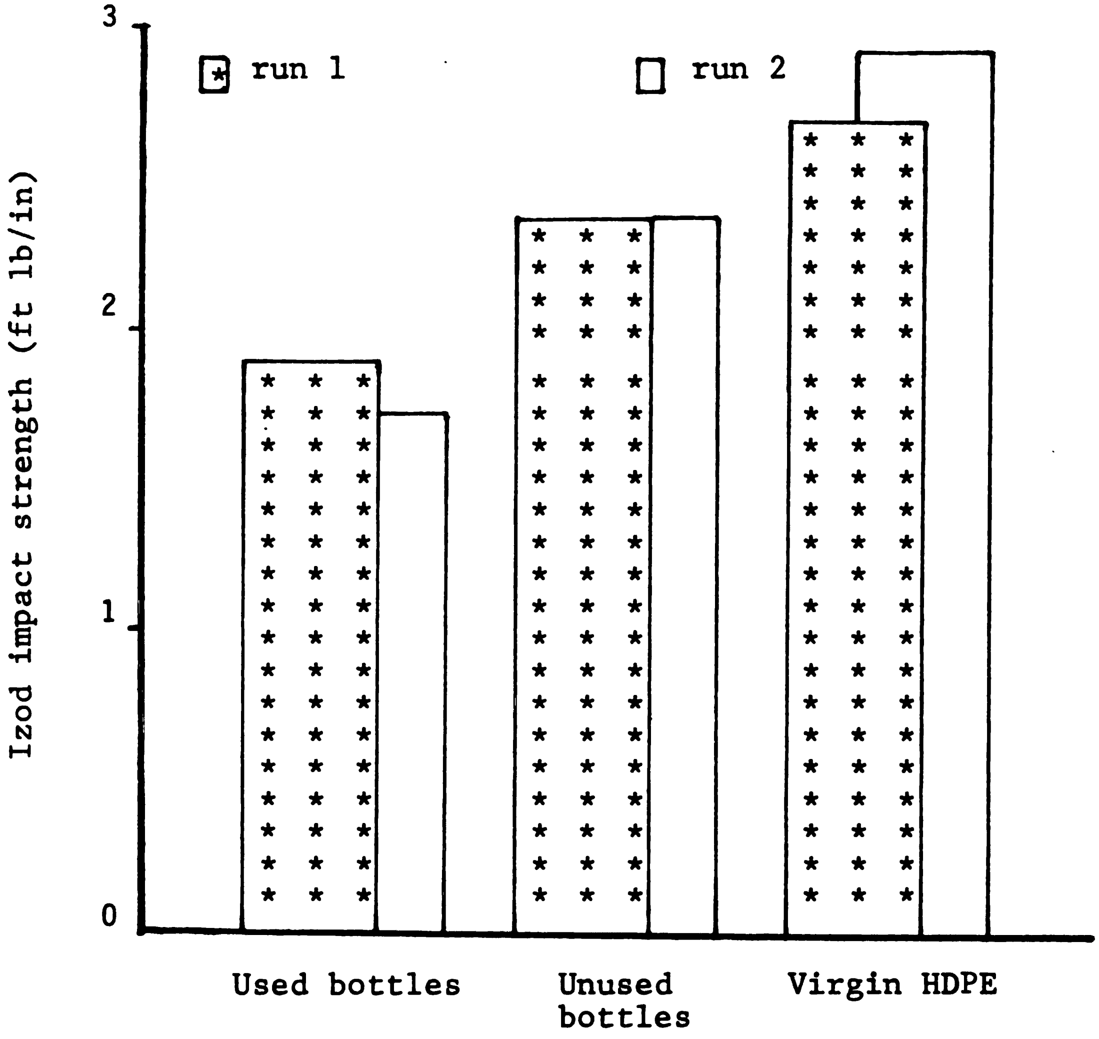


Figure 8: Effect of used cycle on Izod impact strength.

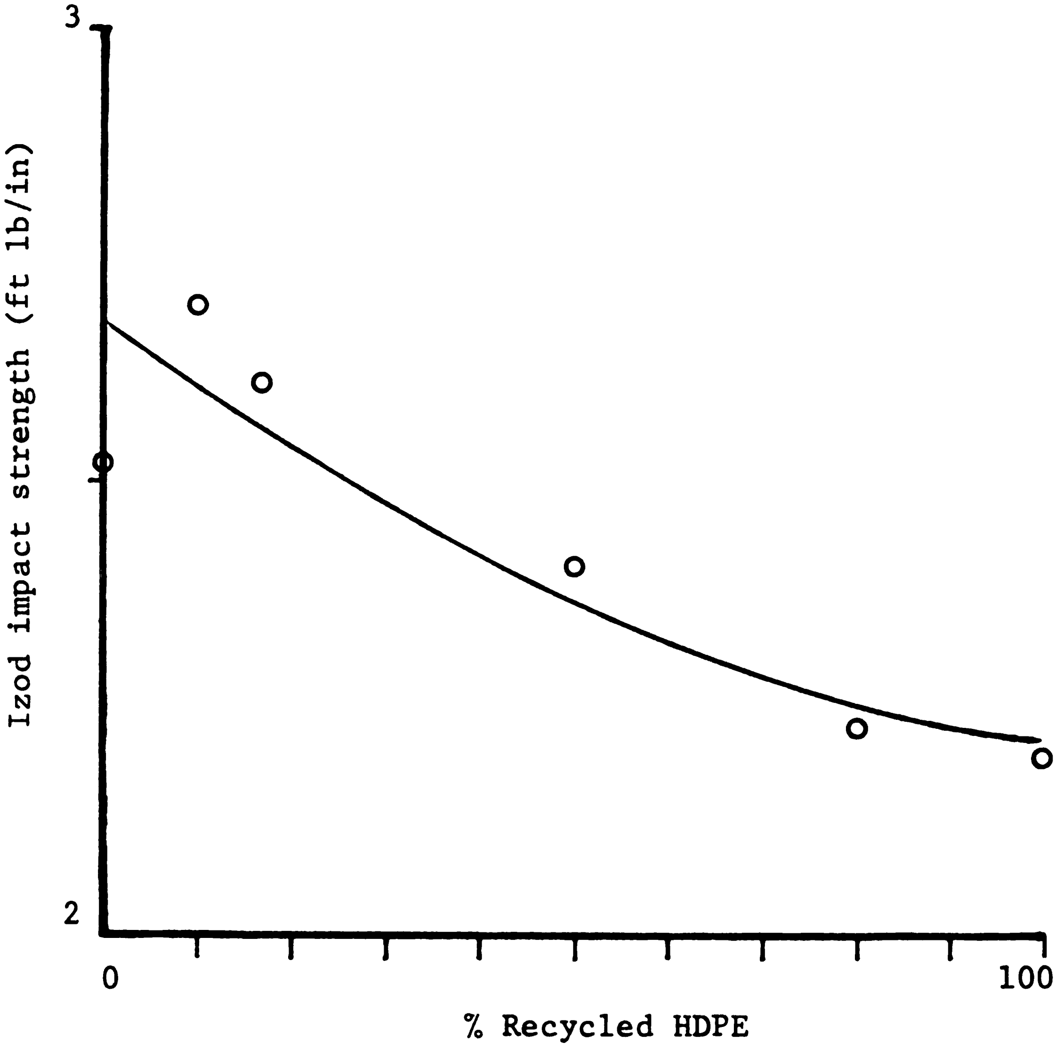


Figure 9: Izod impact strength comparisons

## E. DATA ANALYSIS

To evaluate the significance of changes in properties between virgin, recycled and blended materials, we used Analysis of Variance (ANOVA) at the 95% and 99% confidence levels. Tensile strength, Elongation at yield, and Modulus of elasticity of all treatments showed no significant differences. Elongation at break and Izod impact strength did show significant differences between treatments both at the 95% and 99% confidence levels. Results are summarized in Table 12.

## TABLE 12

## ANALYSIS OF VARIANCE

## FOR MIXTURES OF VIRGIN AND RECYCLED HDPE

| Variable | d.f. | F-value | Prob. | significance level | |
|---|---|---|---|---|---|
| | | | | 0.05 | 0.01 |
| Tensile strength | | | | | |
| run 1 | 5 | 1.23 | .329 | ns. | ns. |
| run 2 | 5 | 1.33 | .285 | ns. | ns. |
| Elongation at break | | | | | |
| run 1 | 5 | 4.57 | .004 | * | ** |
| run 2 | 5 | 12.79 | .000 | * | ** |
| Elongation at yield | | | | | |
| run 1 | 5 | 1.23 | .326 | ns. | ns. |
| run 2 | 5 | 0.25 | - | ns. | ns. |
| Modulus of elasticity | | | | | |
| run 1 | 5 | 1.72 | .170 | ns. | ns. |
| run 2 | 5 | 1.85 | .143 | ns. | ns. |
| Izod impact strength | 5 | 9.00 | .000 | * | ** |

## V. SUMMARY AND CONCLUSIONS

Recycled HDPE milk bottles have been changed in some mechanical and physical properties due to polymer degradation and contamination. The Elongation at break and Izod impact strength are the most sensitive properties to detect the inferiority of recycled materials compared to virgin materials. Moreover, both properties have similar behaviors for mixtures of virgin and recycled HDPE. These observations may be useful for predicting one property from another. Other properties such as MFI, tensile strength, elongation at yield and modulus of elasticity showed little or no change.

The estimation of changes in MWD by the MFI technique was not effective in this case, as we could not detect differences between virgin and recycled materials, although the mechanical properties illustrated that there were changes in the polymer.

## VI. SUGGESTIONS FOR FURTHER WORK

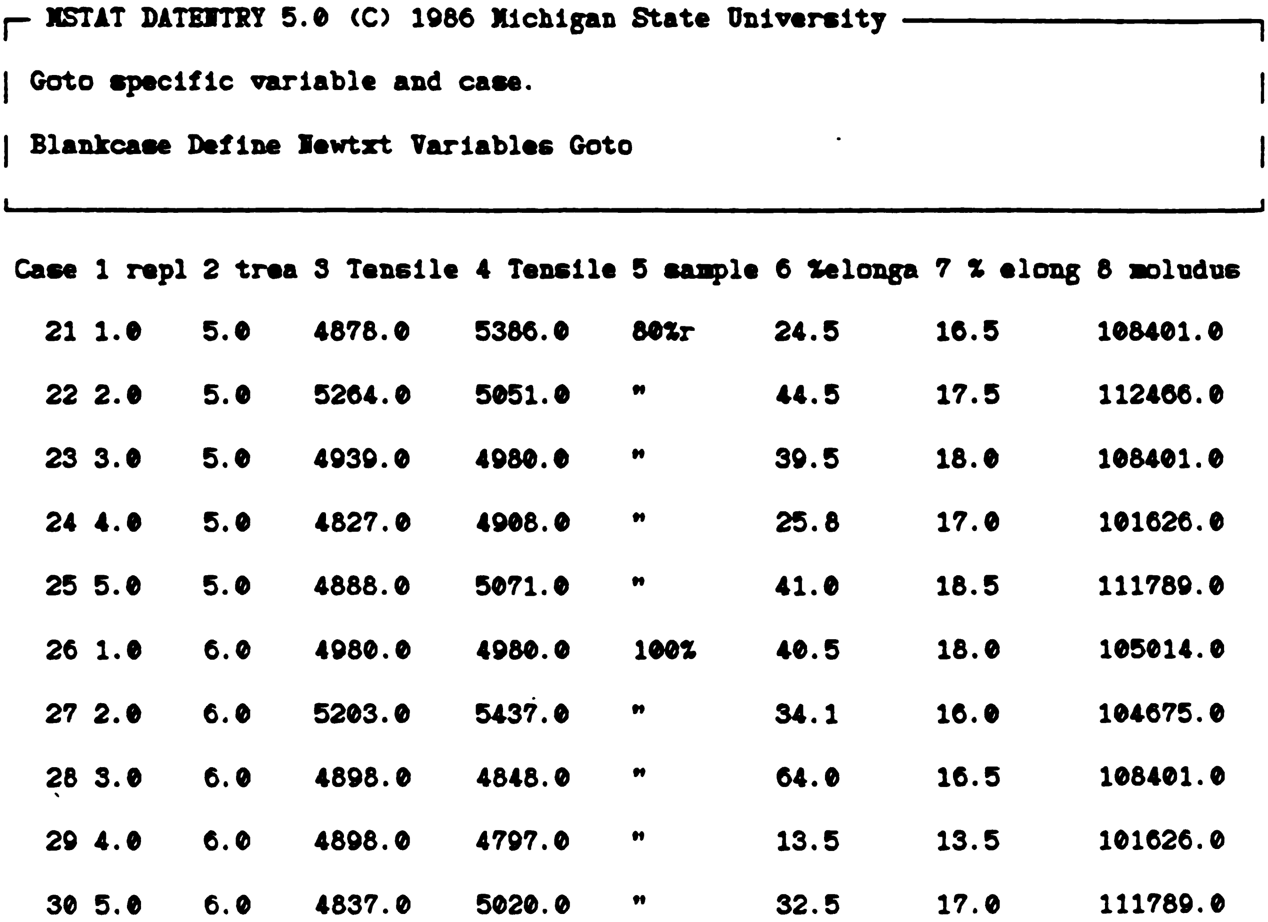
The suggestions about MW and MWD changes that are provided in this paper should be confirmed by gel permeation chromatography which is not presently available in the School of Packaging, Michigan State University. Other properties that should be studied are stress crack resistance, material lifetime (aging, weathering, etc.) and brittleness temperature.

# APPENDIX A

# DATA AND ANALYSIS OF VARIANCE

```
                         A N O V A - 1
                         one way ANOVA
                rev.  10/10/85  MSTAT Version 4.00/EM
                  Revised by Scott P. Eisensmith



DO YOU WANT A LIST OF THE VARIABLES DISPLAYED ON THE SCREEN? (Y or N)


                       LIST OF VARIABLES


VAR TYPE    NAME/DESCRIPTION

  1 numeric replications

  2 numeric treatment

  3 numeric Tensile strength run 1

  4 numeric Tensile strength run 2

  5 text   4 sample description

  6 numeric %elongation at break run 1

  7 numeric % elongation at yield run 1

  8 numeric moludus of elasticity run 1

  9 numeric modulus of elasticity run 2

 10 numeric %elongation at break run 2

 11 numeric % elongation at yield run 2


PRESS RETURN TO CONTINUE
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ──────────────┐
| Choose specific variables to be edited.                              |
| Blankcase Define Newtxt Variables Goto                               |
└──────────────────────────────────────────────────────────────────────┘

Case 1 repl 2 trea 3 Tensile 4 Tensile 5 sample 6 %elonga 7 % elong 8 moludus
   1 1.0    1.0     5163.0    4817.0    0%re     84.0      17.5      106707.0
   2 2.0    1.0     4827.0    4756.0    "        59.5      17.5      109756.0
   3 3.0    1.0     4756.0    4695.0    "        57.5      16.0      109756.0
   4 4.0    1.0     4837.0    4817.0    "        56.5      15.5      106707.0
   5 5.0    1.0     4878.0    4827.0    "        91.0      18.5      101626.0
   6 1.0    2.0     4756.0    4817.0    10%r     61.3      17.0      102642.0
   7 2.0    2.0     4776.0    5163.0    "        61.8      17.5      99085.0
   8 3.0    2.0     4878.0    5081.0    "        52.5      19.0      101626.0
   9 4.0    2.0     4878.0    4898.0    "        58.5      19.0      105014.0
  10 5.0    2.0     4878.0    4827.0    "        79.5      17.5      101626.0
  11 1.0    3.0     4827.0    5203.0    20%r     38.8      17.5      96545.0
  12 2.0    3.0     4827.0    4888.0    "        40.7      17.5      105014.0
  13 3.0    3.0     4827.0    4675.0    "        53.5      16.0      101626.0
  14 4.0    3.0     4726.0    5081.0    "        56.0      14.5      111789.0
  15 5.0    3.0               4797.0    "
  16 1.0    4.0     4868.0    4980.0    50%r     31.8      17.5      101626.0
  17 2.0    4.0     5061.0    4959.0    "        40.3      14.0      108401.0
  18 3.0    4.0     4787.0    5386.0    "        73.5      18.0      98238.0
  19 4.0    4.0     4898.0    4898.0    "        35.0      17.5      104675.0
  20 5.0    4.0     4878.0    4726.0    "        64.0      18.0      106707.0
```



```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ──────────────┐
| Goto specific variable and case.                                     |
| Blankcase Define Newtxt Variables Goto                               |
└──────────────────────────────────────────────────────────────────────┘

Case 1 repl 2 trea 3 Tensile 4 Tensile 5 sample 6 %elonga 7 % elong 8 moludus
  21 1.0    5.0    4878.0    5386.0    80%r     24.5      16.5      108401.0
  22 2.0    5.0    5264.0    5051.0    "        44.5      17.5      112466.0
  23 3.0    5.0    4939.0    4980.0    "        39.5      18.0      108401.0
  24 4.0    5.0    4827.0    4908.0    "        25.8      17.0      101626.0
  25 5.0    5.0    4888.0    5071.0    "        41.0      18.5      111789.0
  26 1.0    6.0    4980.0    4980.0    100%     40.5      18.0      105014.0
  27 2.0    6.0    5203.0    5437.0    "        34.1      16.0      104675.0
  28 3.0    6.0    4898.0    4848.0    "        64.0      16.5      108401.0
  29 4.0    6.0    4898.0    4797.0    "        13.5      13.5      101626.0
  30 5.0    6.0    4837.0    5020.0    "        32.5      17.0      111789.0
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ─────────
| Choose specific variables to be edited.
| Blankcase Define Newtxt Variables Goto
└─────────────────────────────────────────────────────────────────

Case 5 sample 9 modulus  10 %elong 11 % elon
   1 0%re     76219.0    87.0      17.6
   2 "        86382.0    85.2      18.0
   3 "        86382.0    72.0      15.8
   4 "        86382.0    110.0     17.6
   5 "
   6 10%r     81301.0    54.2      17.4
   7 "        76219.0    62.6      17.6
   8 "        91463.0    60.4      17.6
   9 "        106707.0   72.4      17.2
  10 "        87398.0    62.4      16.0
  11 20%r     76219.0    58.6      18.4
  12 "        101626.0   35.6      17.4
  13 "        71138.0    55.0      16.4
  14 "        96545.0    41.4      17.8
  15 "        76219.0    66.0      18.0
  16 50%r     91463.0    22.0      18.0
  17 "        96545.0    35.2      16.0
  18 "        96545.0    61.6      18.0
  19 "        88923.0    26.0      17.8
  20 "        86382.0    62.4      17.0
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ──────────
| Goto specific variable and case.
| Blankcase Define Newtxt Variables Goto                          .
└──────────────────────────────────────────────────────────────────

Case 5 sample 9 modulus  10 %elong 11 % elon
  21 80%r
  22 "        101626.0  22.0      16.4
  23 "        86382.0   43.2      16.8
  24 "        91463.0   32.8      17.6
  25 "        127032.0  40.2      17.8
  26 100%     101626.0  29.2      17.8
  27 "        111789.0  36.0      17.6
  28 "        86382.0   26.8      17.2
  29 "        91463.0   35.4      17.0
  30 "        101626.0  26.0      17.2
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  3

Tensile strength run 1


A N A L Y S I S    O F    V A R I A N C E    T A B L E


        Degrees of         Sum of          Error

            Freedom          Squares      Mean Square   F-value   Prob.

-----------------------------------------------------------------------

Between     5          97829.8845       19565.98       1.23     .329

Within     23         367141.1500       15962.66

-----------------------------------------------------------------------

Total      28         464971.0345

-----------------------------------------------------------------------


Coefficient of Variation=    2.58%
```

```
Var.     V A R I A B L E  No.   3

  2    Number      Sum  Average       SD      SE

--------------------------------------------------

  1      5.00  24461.000   4892.20   157.63   56.50

  2      5.00  24166.000   4833.20    61.75   56.50

  3      4.00  19207.000   4801.75    50.50   63.17

  4      5.00  24492.000   4898.40   100.24   56.50

  5      5.00  24796.000   4959.20   174.96   56.50

  6      5.00  24816.000   4963.20   143.37   56.50

--------------------------------------------------

Total   29.00 141938.000   4894.41   128.86   23.93

Within                              126.34


Bartlett's Test

---------------

Chi-square =  6.979116

Number of Degrees of Freedom =  5

Approximate Significance = .2221
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  4

Tensile strength run 2


A N A L Y S I S   O F   V A R I A N C E   T A B L E


      Degrees of         Sum of         Error
         Freedom        Squares      Mean Square   F-value   Prob.
-------------------------------------------------------------------

Between    5        253971.3667      50794.27         1.33     .285

Within    24        917225.6000      38217.73
-------------------------------------------------------------------

Total     29       1171196.9667
-------------------------------------------------------------------


Coefficient of Variation=    3.94%
```

```
Var.      V A R I A B L E  No.   4

  2     Number       Sum  Average      SD      SE

-----------------------------------------------------

  1       5.00  23912.000   4782.40    56.39   87.43

  2       5.00  24786.000   4957.20   156.36   87.43

  3       5.00  24644.000   4928.80   213.19   87.43

  4       5.00  24949.000   4989.80   242.92   87.43

  5       5.00  25396.000   5079.20   183.12   87.43

  6       5.00  25082.000   5016.40   252.36   87.43

-----------------------------------------------------

Total    30.00 148769.000   4958.97   200.96   36.69

Within                                195.49


Bartlett's Test

---------------

Chi-square =  7.092797

Number of Degrees of Freedom =  5

Approximate Significance = .2138
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  6

%elongation at break run 1


A N A L Y S I S    O F    V A R I A N C E    T A B L E


      Degrees of          Sum of          Error

         Freedom          Squares       Mean Square   F-value   Prob.

------------------------------------------------------------------

Between     5        4753.8107         950.76        4.57      .004

Within     23        4780.1139         207.83

------------------------------------------------------------------

Total      28        9533.9246

------------------------------------------------------------------


Coefficient of Variation=   28.73%
```

```
Var.     V A R I A B L E  No.   6

  2    Number      Sum  Average      SD     SE
------------------------------------------------

  1      5.00   348.500    69.70   16.47   6.45

  2      5.00   313.500    62.70   10.09   6.45

  3      4.00   188.950    47.24    8.77   7.21

  4      5.00   244.550    48.91   18.67   6.45

  5      5.00   175.300    35.06    9.24   6.45

  6      5.00   184.600    36.92   18.18   6.45
------------------------------------------------

Total   29.00  1455.400    50.19   18.45   3.43

Within                             14.42


Bartlett's Test
---------------

Chi-square =  3.999969

Number of Degrees of Freedom =  5

Approximate Significance = .5494
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  7

% elongation at yield run 1


A N A L Y S I S    O F    V A R I A N C E    T A B L E


      Degrees of          Sum of          Error

         Freedom          Squares       Mean Square   F-value   Prob.

-----------------------------------------------------------------------

Between      5            10.9780            2.20        1.23      .326

Within      23            40.9875            1.78

-----------------------------------------------------------------------

Total       28            51.9655

-----------------------------------------------------------------------


Coefficient of Variation=     7.84%
```

```
 Var.     V A R I A B L E  No.   7

   2    Number       Sum   Average      SD      SE
------------------------------------------------------

   1     5.00     85.000     17.00    1.22    0.60

   2     5.00     90.000     18.00    0.94    0.60

   3     4.00     65.500     16.38    1.44    0.67

   4     5.00     85.000     17.00    1.70    0.60

   5     5.00     87.500     17.50    0.79    0.60

   6     5.00     81.000     16.20    1.68    0.60

------------------------------------------------------

Total   29.00    494.000     17.03    1.36    0.25

Within                                1.33


Bartlett's Test

---------------

Chi-square =  3.202316

Number of Degrees of Freedom =  5

Approximate Significance = .6688
```

```
Data file         HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection




One way ANOVA grouped over variable  2

treatment

with values from 1  to  6




Variable  8

moludus of elasticity run 1


A N A L Y S I S    O F    V A R I A N C E    T A B L E


      Degrees of          Sum of           Error

         Freedom          Squares        Mean Square  F-value   Prob.
------------------------------------------------------------------

Between     5   143930416.0621   28786083.21        1.72     .170

Within     23   385581625.8000   16764418.51
------------------------------------------------------------------

Total      28   529512041.8621
------------------------------------------------------------------


Coefficient of Variation=    3.89%
```

```
Var.      V A R I A B L E  No.   8

   2    Number       Sum  Average      SD      SE
-----------------------------------------------------

   1     5.00 534552.000 106910.40  3324.25 1831.09

   2     5.00 509993.000 101998.60  2137.37 1831.09

   3     4.00 414974.000 103743.50  6393.92 2047.22

   4     5.00 519647.000 103929.40  4060.91 1831.09

   5     5.00 542683.000 108536.60  4295.68 1831.09

   6     5.00 531505.000 106301.00  3895.00 1831.09

-----------------------------------------------------

Total    29.00 %3053354.000 105288.07  4348.69  807.53

Within                                4094.44


Bartlett's Test

---------------

Chi-square =  3.876682

Number of Degrees of Freedom =  5

Approximate Significance = .5673
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  9

modulus of elasticity run 2


A N A L Y S I S   O F   V A R I A N C E   T A B L E


      Degrees of          Sum of          Error

         Freedom          Squares       Mean Square  F-value   Prob.
-------------------------------------------------------------------

Between     5   1193258662.2071   238651732.44       1.85     .143

Within     22   2831730373.9000   128715017.00
-------------------------------------------------------------------

Total      27   4024989036.1071
-------------------------------------------------------------------


Coefficient of Variation=   12.41%
```

```
 Var.     V  A  R  I  A  B  L  E  No.   9

   2    Number      Sum  Average       SD      SE
----------------------------------------------------

   1      4.00 335365.000  83841.25  5081.50 5672.63

   2      5.00 443088.000  88617.60 11662.63 5073.76

   3      5.00 421747.000  84349.40 13729.18 5073.76

   4      5.00 459858.000  91971.60  4545.00 5073.76

   5      4.00 406503.000 101625.75 18084.35 5672.63

   6      5.00 492886.000  98577.20  9905.51 5073.76
----------------------------------------------------

Total    28.00 %2559447.000  91408.82 12209.57 2307.39

Within                              11345.26


Bartlett's Test
---------------

Chi-square =  7.832493

Number of Degrees of Freedom =  5

Approximate Significance = .1657
```

```
Data file        HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  10

%elongation at break run 2


A N A L Y S I S   O F   V A R I A N C E   T A B L E


      Degrees of          Sum of          Error
         Freedom         Squares      Mean Square   F-value   Prob.
-------------------------------------------------------------------
Between    5          9892.7489        1978.55      12.79     .000

Within    22          3404.5081         154.75
-------------------------------------------------------------------
Total     27         13297.2570
-------------------------------------------------------------------


Coefficient of Variation=   24.50%
```

```
Var.       V A R I A B L E  No.   10

  2    Number      Sum   Average      SD      SE
------------------------------------------------

  1      4.00   354.200    88.55   15.79    6.22

  2      5.00   312.000    62.40    6.54    5.56

  3      5.00   256.600    51.32   12.53    5.56

  4      5.00   207.200    41.44   19.37    5.56

  5      4.00   138.200    34.55    9.44    6.22

  6      5.00   153.400    30.68    4.74    5.56

------------------------------------------------

Total   28.00  1421.600    50.77   22.19    4.19

Within                             12.44


Bartlett's Test

---------------

Chi-square =  8.567118

Number of Degrees of Freedom =  5

Approximate Significance = .1276
```

```
Data file       HDPE

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  30

Without selection



One way ANOVA grouped over variable  2

treatment

with values from 1  to  6



Variable  11

% elongation at yield run 2


A N A L Y S I S   O F   V A R I A N C E   T A B L E


      Degrees of        Sum of         Error

         Freedom        Squares      Mean Square   F-value   Prob.
-----------------------------------------------------------------

Between    5            0.6711          0.13        0.25

Within    22           11.7560          0.53
-----------------------------------------------------------------

Total     27           12.4271
-----------------------------------------------------------------


Coefficient of Variation=   4.22%
```

```
  Var.      V  A  R  I  A  B  L  E  No.   11

    2     Number      Sum   Average      SD     SE

 ----------------------------------------------------

    1      4.00    69.000     17.25    0.98   0.37

    2      5.00    85.800     17.16    0.67   0.33

    3      5.00    88.000     17.60    0.76   0.33

    4      5.00    86.800     17.36    0.86   0.33

    5      4.00    68.600     17.15    0.66   0.37

    6      5.00    86.800     17.36    0.33   0.33

 ----------------------------------------------------

 Total    28.00   485.000     17.32    0.68   0.13

 Within                                0.73


 Bartlett's Test

 ---------------

 Chi-square =  3.830831

 Number of Degrees of Freedom =  5

 Approximate Significance = .574
```

```
                      A N O V A - 1

                      one way ANOVA

                 rev.  10/10/85  MSTAT Version 4.00/EM

                    Revised by Scott P. Eisensmith



DO YOU WANT A LIST OF THE VARIABLES DISPLAYED ON THE SCREEN? (Y or N) y


                    LIST OF VARIABLES


VAR TYPE    NAME/DESCRIPTION

  1 numeric replications

  2 numeric treatments

  3 text   4 sample discriptions

  4 numeric Izod impact strength


PRESS RETURN TO CONTINUE
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ─────────────
| File command menu
| File Edit Quit
└──────────────────────────────────────────────────────────────────────

Case 1 r 2 t 3 sample 4 Izo
   1 1.0 1.0 0%re     2.663
   2 2.0 1.0 "        2.694
   3 3.0 1.0 "        2.555
   4 4.0 1.0 "        2.619
   5 5.0 1.0 "        2.588
   6 6.0 1.0 "        2.444
   7 7.0 1.0 "        2.399
   8 8.0 1.0 "        2.217
   9 1.0 2.0 10%r     2.513
  10 2.0 2.0 "        3.006
  11 3.0 2.0 "        2.836
  12 4.0 2.0 "        2.841
  13 5.0 2.0 "        2.705
  14 6.0 2.0 "        2.264
  15 7.0 2.0 "        2.446
  16 8.0 2.0 "        2.935
  17 1.0 3.0 16.7     2.420
  18 2.0 3.0 "        2.553
  19 3.0 3.0 "        2.702
  20 4.0 3.0 "        2.595
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ──────────
| Editing command menu.
| File Edit Quit
└──────────────────────────────────────────────────────────────────

Case 1 r 2 t 3 sample 4 Izo
  21 5.0 3.0 "         2.608
  22 6.0 3.0 "         2.597
  23 7.0 3.0 "         2.464
  24 8.0 3.0 "         2.927
  25 1.0 4.0 50%r      2.491
  26 2.0 4.0 "         2.337
  27 3.0 4.0 "         2.132
  28 4.0 4.0 "         2.582
  29 5.0 4.0 "         2.499
  30 6.0 4.0 "         2.359
  31 7.0 4.0 "         2.469
  32 8.0 4.0 "         2.400
  33 1.0 5.0 80%r      2.555
  34 2.0 5.0 "         1.877
  35 3.0 5.0 "         2.138
  36 4.0 5.0 "         2.243
  37 5.0 5.0 "         2.468
  38 6.0 5.0 "         2.267
  39 7.0 5.0 "         1.942
  40 8.0 5.0 "         2.359
```

```
┌─ MSTAT DATENTRY 5.0 (C) 1986 Michigan State University ──────────
| Editing command menu.
| File Edit Quit
└──────────────────────────────────────────────────────────────────

Case 1 r 2 t 3 sample 4 Izo
  41 1.0 6.0 100%     2.214
  42 2.0 6.0 "        2.201
  43 3.0 6.0 "        2.178
  44 4.0 6.0 "        1.902
  45 5.0 6.0 "        2.286
  46 6.0 6.0 "        2.379
  47 7.0 6.0 "        2.310
  48 8.0 6.0 "        2.138
```

```
Data file    HDPE-2

Title: Mechanical evaluation of HDPE


Function: ANOVA-1

Data case no.  1  to  48

Without selection



One way ANOVA grouped over variable  2

treatments

with values from 1  to  6



Variable  4

Izod impact strength


A N A L Y S I S   O F   V A R I A N C E   T A B L E


      Degrees of         Sum of         Error
         Freedom        Squares     Mean Square  F-value   Prob.
-----------------------------------------------------------------

Between     5           1.6069          0.32        9.00     .000

Within     42           1.4992          0.04
-----------------------------------------------------------------

Total      47           3.1061
-----------------------------------------------------------------


Coefficient of Variation=    7.73%
```

```
Var.     V A R I A B L E  No.  4

  2   Number     Sum  Average     SD    SE

-----------------------------------------

  1     8.00   20.179     2.52   0.16  0.07

  2     8.00   21.546     2.69   0.26  0.07

  3     8.00   20.866     2.61   0.16  0.07

  4     8.00   19.269     2.41   0.14  0.07

  5     8.00   17.849     2.23   0.24  0.07

  6     8.00   17.608     2.20   0.14  0.07

-----------------------------------------

Total  48.00  117.317     2.44   0.26  0.04

Within                           0.19


Bartlett's Test

---------------

Chi-square =  5.245091

Number of Degrees of Freedom =  5

Approximate Significance = .3867
```

# APPENDIX B

# TYPICAL GRAPHS AND APPEARANCES OF SPECIMENS OF TENSILE TEST

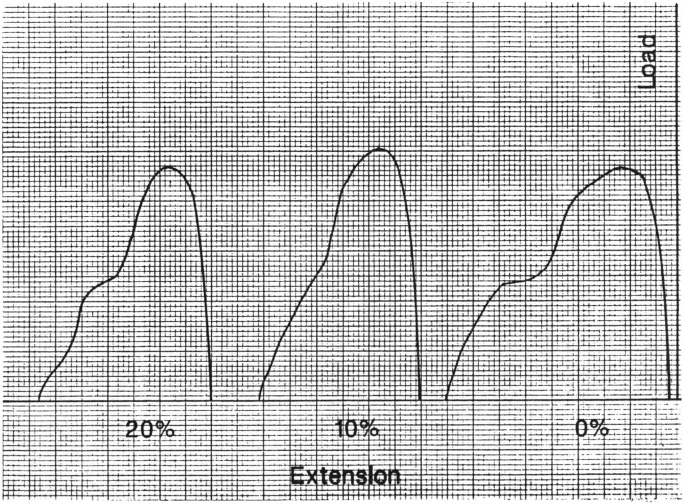


Figure 10: Typical graphs of Tensile test of 0, 10, 20% recycled HDPE in the blends.

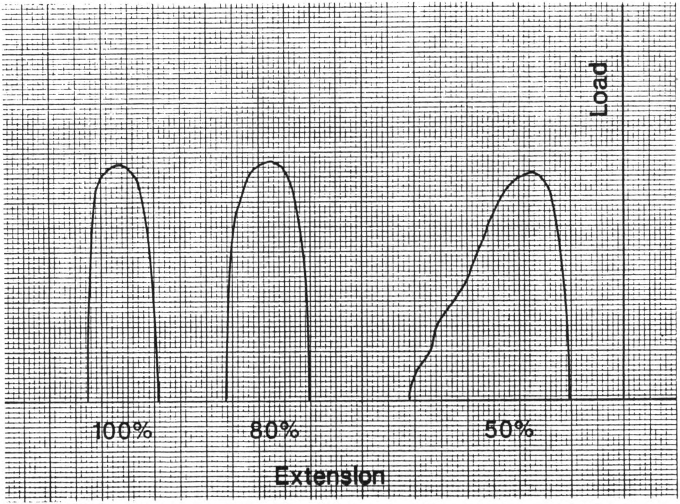


Figure 11: Typical graphs of Tensile test of 50, 80, and 100% recycled HDPE in the blends.

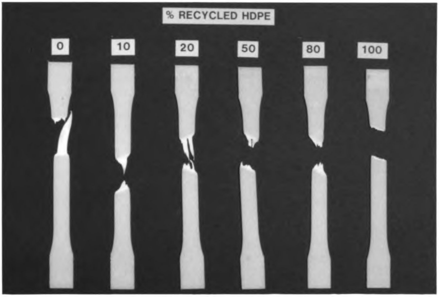


Figure 12: Appearances of specimens after Tensile test

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