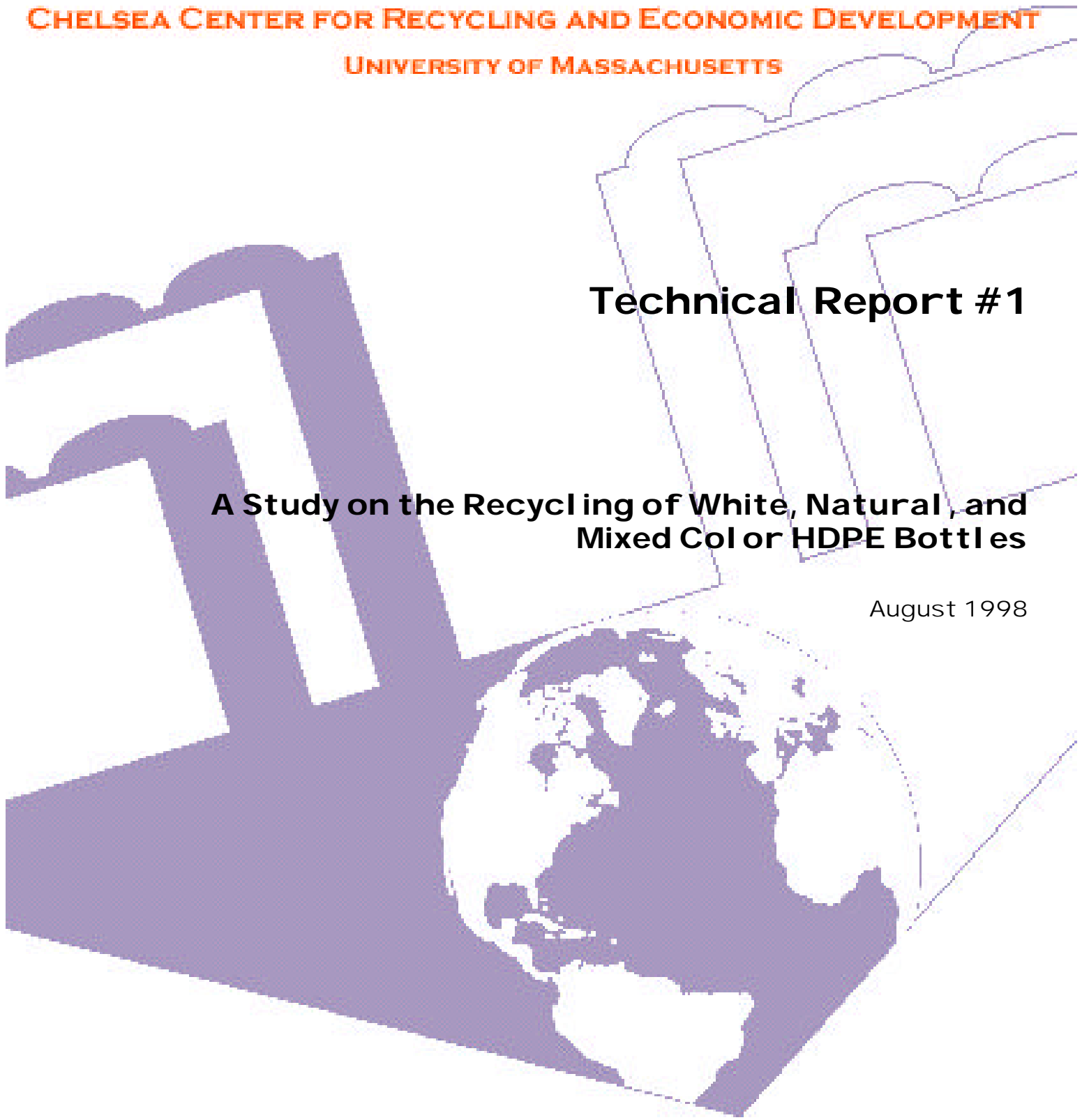


**Technical Report #1**

**A Study on the Recycling of White, Natural, and  
Mixed Color HDPE Bottles**

August 1998



# **A Study on the Recycling of White, Natural , and Mixed Color HDPE Bottles**

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## **Chelsea Center for Recycling and Economic Development Technical Research Program**

August 1998

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## Table of Contents

Acknowledgments	2
Introduction	3
1. Study 1: The Effect of Multiple Recycle Histories on the Properties of Pigmented HDPE Homopolymer Bottle Flake and Natural HDPE Homopolymer Bottle Flake	4
1.1 Scope	4
1.2 Experimental Materials and Procedures	4
1.3 Results	6
1.4 Conclusions	10
2. Study 2: A Study on the Pigmentability of Natural, Mixed Color, and White HDPE	13
2.1 Scope	13
2.2 Experimental Materials and Procedures	13
2.3 Results	15
2.4 Conclusions	16
3. Study 3: The Effect of White HDPE Homopolymer Bottle Flake on the Properties of Natural HDPE Homopolymer Bottle Flake	18
3.1 Scope	18
3.2 Experimental Materials and Procedures	18
3.3 Results	18
3.4 Conclusions	20
4. Study 4: The Effect of White HDPE Homopolymer Bottle Flake on the Properties of Mixed Color HDPE Bottle Flake	22
4.1 Scope	22
4.2 Experimental Materials and Procedures	22
4.3 Results	23
4.4 Conclusions	24
5. Study 5: A Study on the Pigmentability of Natural and White HDPE Blends and Mixed Color and White HDPE Blends	28
5.1 Scope	28
5.2 Experimental Materials and Procedures	28
5.3 Results	30
5.4 Conclusions	30

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## Introduction

The recent introduction of white (pigmented) high-density polyethylene (HDPE) milk bottles (with enhanced light blocking capability) has raised a number of technical and economic issues associated with the white containers' recyclability. After use, these white HDPE containers can become a component of the postconsumer waste stream, like most HDPE bottles. While a very large percentage of postconsumer natural (unpigmented) and mixed color HDPE bottles are recycled on a routine basis, the recyclability (or recycling methodology) of this relatively new white HDPE bottle waste stream has become an issue in the HDPE recycling community.

At this point, established collectors and recyclers of HDPE bottles have several possible options for dealing with the white HDPE postconsumer bottles, including:

- Treating the white HDPE homopolymer milk bottles as a separate HDPE waste stream for resale as white flake or pellets.
- Creating a commingled (mixed) stream of white and natural HDPE homopolymer for resale as flake or pellets.
- Incorporating the white HDPE homopolymer into the mixed color<sup>1</sup> HDPE (homopolymer and copolymer) waste stream.

To help address questions concerning the recycling of white postconsumer HDPE milk bottle scrap, the Department of Plastics Engineering at the University of Massachusetts in Lowell conducted five separate studies for the Chelsea Center for Recycling and Economic Development. This report presents the results of these studies. Together, this work represents an effort to provide quantitative data concerning the recycling of white postconsumer HDPE bottle scrap and to address several of the issues associated with the recycling of this material. The quantitative data generated in this study is designed to assist HDPE bottle recyclers in determining the best recycling options for the pigmented HDPE bottle.

The majority of these studies focus on the physical characteristics of the recycled materials. There also are technical and economic issues associated with each of these recycling options for the white HDPE bottle. This study does not attempt to address the economic issues associated with each option; however, a number of the technical issues associated with each of the three recycling options are discussed in this report.

Several of the studies in this report involve the preparation and testing of pigmented HDPE samples. These color test results are provided in a table format within this document. In addition, a set of the molded, pigmented HDPE samples has also been prepared and is available for inspection at the Chelsea Center for Recycling and Economic Development.

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<sup>1</sup>Note that most HDPE bottle scrap recyclers process two HDPE bottle waste streams. The first stream is natural HDPE homopolymer bottle scrap. The second stream is the "mixed color" HDPE stream (pigmented copolymer and homopolymer), which is a mixture of all other pigmented HDPE bottles. A limited number of HDPE recyclers perform some additional color sorting procedures for the mixed color HDPE waste stream.

# **1. Study 1: The Effect of Multiple Recycle Histories on the Properties of Pigmented HDPE Homopolymer Bottle Flake and Natural HDPE Homopolymer Bottle Flake**

## **1.1 Scope**

The objective of Study 1 is to determine how the physical properties of HDPE homopolymer bottle flake change when subjected to multiple recycle histories. The study was conducted using white HDPE homopolymer milk bottle flake. Natural HDPE homopolymer bottle flake was used in the study as a conventional reference (control).

In theory, thermoplastic materials such as HDPE homopolymer can be recycled since the changes in state that occur during bottle manufacturing are purely physical (rather than chemical) in nature. The ultimate goal of primary recycling depicted in Figure 1-1 (reuse in the original application), however, is not achieved in the case of most HDPE applications, including milk container applications, for a number of reasons. In practice, the properties of thermoplastics such as HDPE do change when exposed to multiple manufacturing and recycle histories. These changes in the physical properties of the HDPE can be due to changes in the polymer's molecular structure, molecular weight distribution, and/or morphology that occur as a result of processing or the product's end-use service environment (e.g., ultraviolet light exposure, or exposure to chemicals). In addition, physical and/or chemical changes also can occur in reaction to the additives that are blended with the base polymer. Finally, there is always the potential for label adhesive residue and other contamination when dealing with recycled materials. This contamination can be difficult to fully remove via conventional cleaning processes. As a result, recycled thermoplastics like HDPE milk bottles are normally utilized for applications that are less demanding than their original application. This concept of secondary plastics recycling is depicted in Figure 1-2.

It is well known that natural, blow molding grade HDPE homopolymer postconsumer scrap is suitable for secondary recycling, particularly when properly washed and cleaned. Postconsumer HDPE material is widely used for extruded products due to its relatively high melt viscosity (too high for most injection molding applications) with minimal property changes. Study 1 was conducted in an effort to determine how the recyclability of white, pigmented HDPE homopolymer milk bottle scrap compares to that of the more conventional natural HDPE postconsumer bottle scrap. The results of this study are most applicable to the scenario in which the white and natural HDPE homopolymer materials are treated as separate material streams.

## **1.2 Experimental Materials and Procedures**

In this study, both natural HDPE homopolymer bottle flake and white HDPE bottle flake were exposed to multiple recycle histories in an effort to determine or simulate how the physical properties of the materials would be affected by multiple (up to 12) recycle histories.

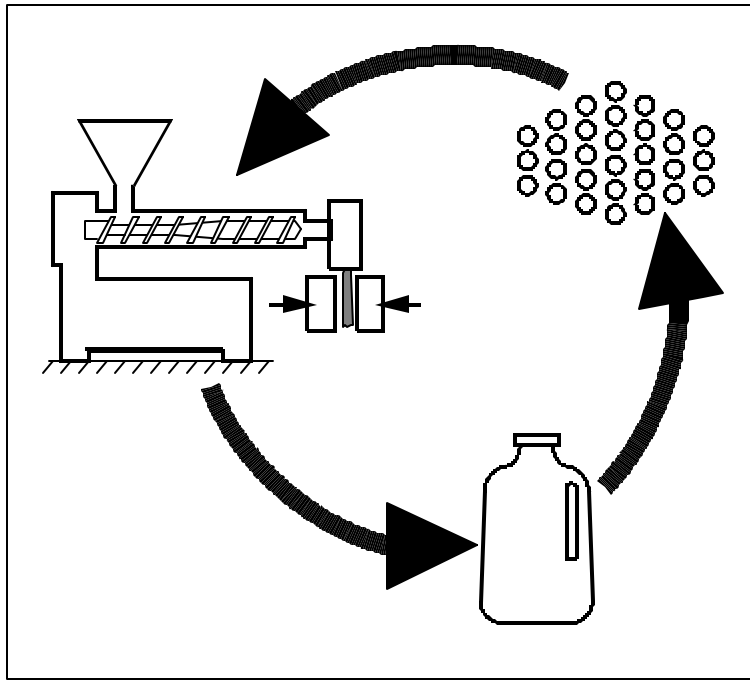


Figure 1-1. Closed-loop (primary) recycling concept.

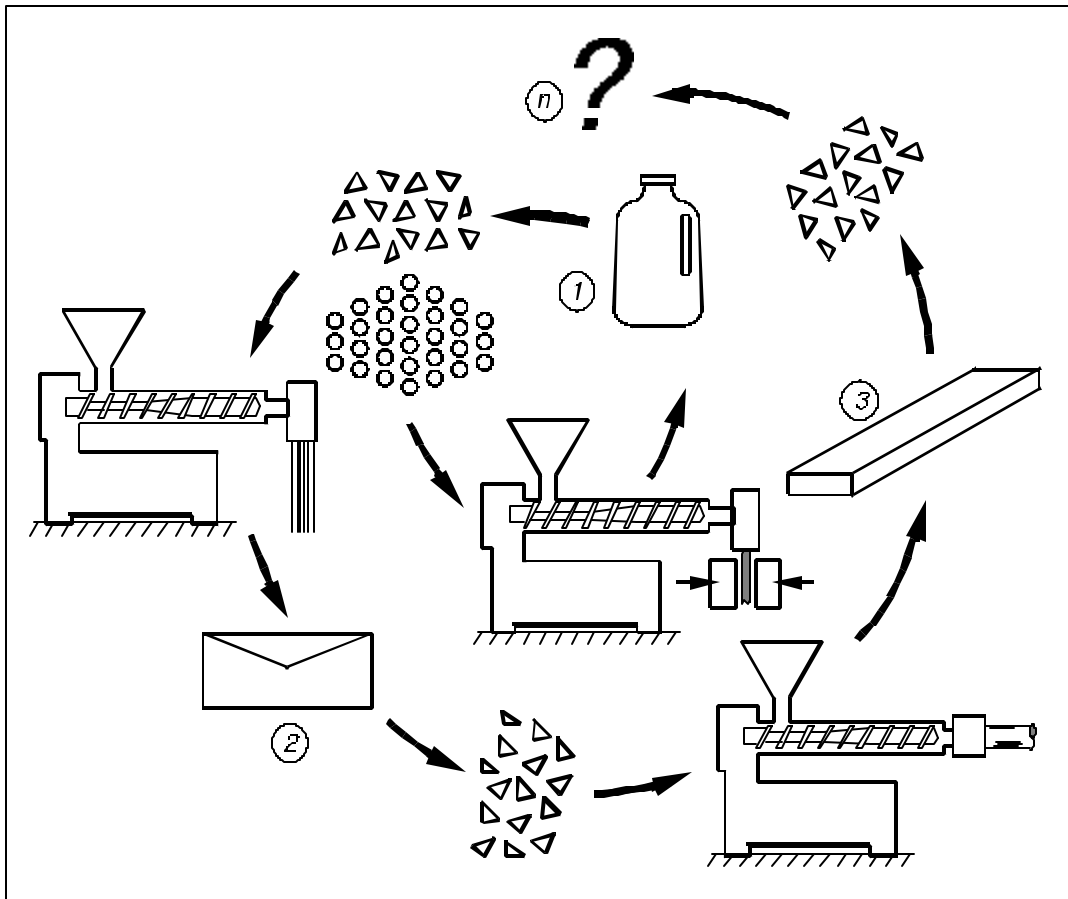


Figure 1-2. The plastics recycling "spiral" or secondary recycling concept. Pellets are manufactured into an HDPE milk bottle (1st use), then into an envelope or bag (2nd use), to plastic lumber or pipe (3rd use), to ? (...nth use).

The materials utilized for the study were:

- Clean, natural HDPE homopolymer postconsumer (repelletized) bottle flake, supplied by EnviroPlastics Corporation, Auburn, Massachusetts.
- Clean, white HDPE homopolymer postindustrial flake, neck, and tail scrap obtained from a milk bottle manufacturing plant, supplied by H.P. Hood Corporation, Chelsea, Massachusetts. The postindustrial material was used in place of the postconsumer material because sufficient quantities of clean, white postconsumer milk bottle flake could not be located commercially when the study was initiated. The white pigment is TiO<sub>2</sub>.

These materials were reprocessed separately (but in an equivalent manner) using a 2 ½ inch diameter, 26 L/D Welex single-screw pelletizing extruder in order to simulate a series of recycle histories (up to 12). The barrel set temperatures during the extrusion process were set to 435°F. The downstream equipment consisted of a water cooling trough for the strands, an air knife to remove excess water, a pelletizer, and a vibrating dryer to ensure the pellets were fully free from moisture. After the first extrusion process (a simulated recycle history), a portion of the extruded pellets was set aside for evaluation. The remaining material was placed back into the hopper of the extruder for an additional extrusion and recycle history. This process was repeated for a number of cycles. Samples were collected for evaluation after the 1st, 2nd, 4th, 8th, and 12th extrusion and simulated recycling process. These retained samples of HDPE pellets were then used to produce standard American Society for Testing and Materials (ASTM) test samples for property evaluation via injection molding using a 22-ton clamp Cincinnati Milacron MC-22 injection molding machine. Both the white and natural HDPE materials were extruded and molded at the same process conditions. The physical property tests conducted on the molded samples (or extruded pellets for ASTM D1238) at the various heat histories included:

- Melt Index (ASTM D1238 at 190°C per 2.16 kg).
- Tensile Properties (ASTM D638 at 2 and 20 inches per minute).
- Izod Impact Resistance (notched ASTM D256 — away from gate).
- Color Measurement (visual observation and spectrophotometer testing — cool fluorescent light simulation at a 10° angle).

The experimental processes used to test the effects of multiple recycle histories, and the equipment and procedures associated with this study, are depicted schematically in Figure 1-3.

### **1.3 Results**

The average physical property test data for both the white and pigmented HDPE and the natural HDPE homopolymer materials are given in Tables 1-1 through 1-7. (Tables for Study 1 begin on page 10.) Throughout this study, average test results are reported, with standard deviation values given in parentheses. The data clearly suggest that both the natural and white HDPE show very good property retention when recycled, even after as many as 12 recycle histories. Both materials retain a high percentage of their original properties, and as such are good material candidates for secondary recycling processes if treated as separate recycle streams.

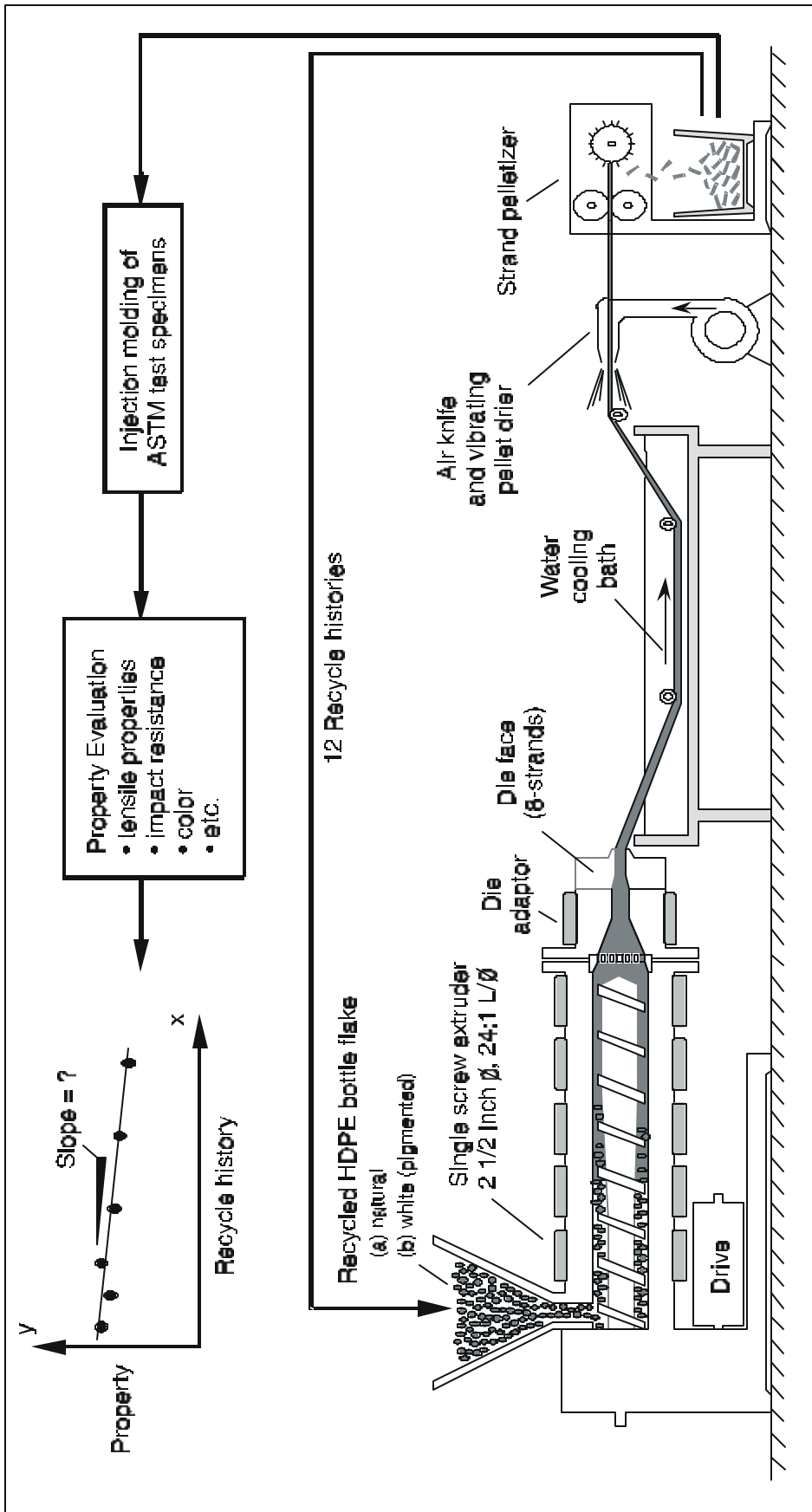


Figure 1-3. Schematic of the experimental equipment used for the recycling history study (Study 1). Samples were taken after 0 ("control"), 1, 2, 4, 8, and 12 recycle and extrusion passes.

The changes in tensile properties associated with recycle history, for example, were generally small, as indicated in Tables 1-1 through 1-4 (5 replicates). The tensile tests were run at two testing speeds (2 and 20 inches per minute), as failure was not observed at the lower testing rate. All tensile modulus and elongation values are based upon the initial gauge length (jaw separation) rather than extensometer measurements. Both materials had similar tensile property behavior, showing similar property values and similar changes with heat history. Consider the tensile yield stress data determined at 2 inches per minute given in Table 1-1 (for natural HDPE) and Table 1-3 (for the white HDPE). The tensile yield strength value for the natural HDPE changes from 3916 psi to 4022 psi after 12 recycle histories, a change of less than 3 percent. The white HDPE yield strength value changes from 3850 psi to 4090 psi after 12 recycle histories, a change of only 6 percent.

The average Izod impact resistance data given in Table 1-5 (10 replicates) indicates impact property retention is also good for both the white and natural HDPE materials; however, the changes in the impact resistances were somewhat more significant than the tensile property changes. This is not unexpected, as impact resistance is very sensitive to such variables as contamination level that are expected to increase with recycle history. Impact resistance is also a property that is sensitive to sampling location. All test data reported were determined using samples taken from the far end (away from the gate) of the test sample. The white HDPE actually exhibited superior impact resistance to that of the natural HDPE. The change in impact resistance with heat history was somewhat less significant for the white HDPE. This is possibly related to the fact that the white HDPE was a cleaner, more homogeneous postindustrial material than the natural postconsumer material, which may contain a degree of adhesive and/or other contamination that would likely have a negative effect on impact performance. In short, impact performance retention was relatively good for both materials.

The data given in Table 1-6 (3 replicates) indicates that the average melt index retention was also quite good for both the white and natural HDPE materials. Melt index is used as an inverse measure of melt viscosity (or resistance to flow) at a very low shear rate. The test can be used to provide an indication of changes in average molecular weight that can occur as a result of recycle history. In each case, the melt index changes were very small, showing no particular trend in any one direction. The melt index values are essentially constant with recycle history. The melt index value for the white HDPE was consistently about 20 percent higher than that of the natural postconsumer HDPE; however, like the natural HDPE, this value showed no significant change with recycle history.

Color changes associated with the recycle histories were evaluated in this study using a spectrophotometer/Hunter L\* - a\* - b\* color coordinate system. (See Figure 1-4 for a graphic depiction of the L\* - a\* - b\* color coordinate system.) This test was not specifically conducted to determine absolute color values for these materials, but rather to determine how their color changes with recycle history. This quantitative color data is given in Table 1-7. Color data can be difficult to obtain and describe universally, as it is affected by many variables. In this case, the simplest way to observe the data given in Table 1-7 is to consider the  $\Delta E^*$  values. This single number provides an indication of the overall color shift that has occurred as a result of the various recycle histories (based on the reference sample having one recycle history). The  $\Delta E^*$  values for the natural HDPE were measurable, but not extremely significant. The color shift of

4.33 over 12 recycle histories is visually detectable (comparing one recycle history to 12 recycle histories). It would be very difficult, however, to detect the change in color associated with just one recycle history. (As a reference,  $\Delta E^*$  value variations in the range of 1.0 or lower are used as an indication of acceptable color quality for many pigmented plastic products during quality control testing.) Similar results were obtained with the white HDPE. In fact, even less of a color shift was observed for the white pigmented HDPE, showing a  $\Delta E^*$  value color shift of only 1.72 over the course of 12 recycle histories. This color shift per recycle history is very low. The pigmented HDPE samples retained their whiteness, as indicated by the relatively small decrease in the  $+L^*$  value with only a fractional increase in the  $+b^*$  value (yellowness) as a result of exposure to 12 recycle histories.

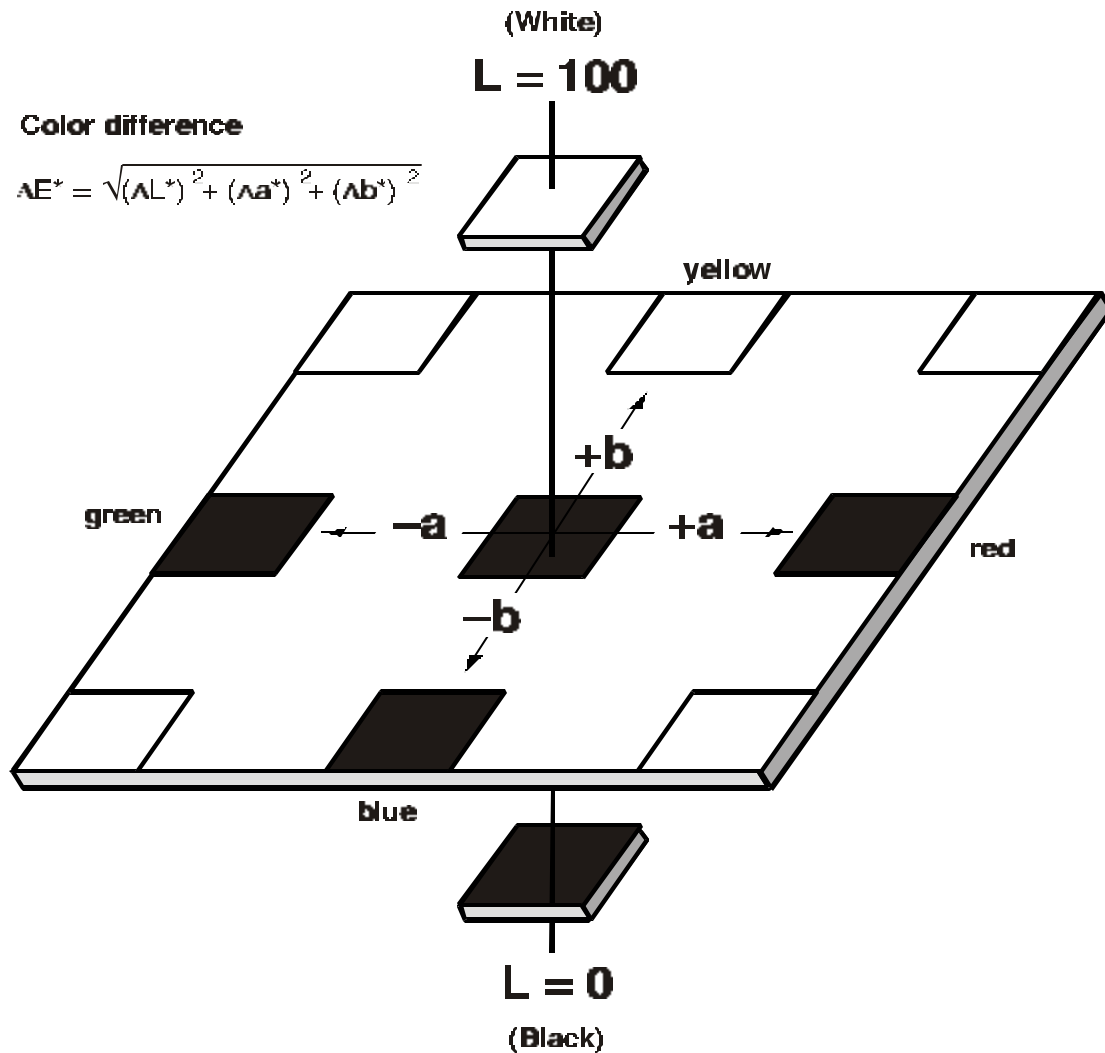


Figure 3-4. The  $L^* - a^* - b^*$  color coordinate system.

## 1.4 Conclusions

If it is assumed that the natural HDPE and white HDPE are treated as separate material streams, then it can be concluded that both the natural HDPE and the white HDPE homopolymer materials are relatively easy to recycle and exhibit excellent property retention, even when subjected to multiple (as many as 12) recycle histories.

**Table 1-1. Tensile Properties of Natural HDPE Versus Recycle History (2 inch/min)\***

<b>Recycle History</b>	<b>Break Stress PSI</b>	<b>Break Elongation Percent</b>	<b>Yield Stress PSI</b>	<b>Yield Elongation Percent</b>	<b>Initial Modulus PSI</b>
1	----- -----	----- -----	3916 (16)	12.7 (0.6)	119700 (3295)
2	----- -----	----- -----	3966 (58)	12.4 (1.4)	121100 (6445)
4	----- -----	----- -----	4016 (37)	11.6 (0.7)	127900 (3211)
8	----- -----	----- -----	4024 (25)	11.8 (0.6)	123700 (2445)
12	----- -----	----- -----	4022 (15)	11.8 (1.2)	122300 (3367)

\*Standard deviation shown in parentheses

**Table 1-2. Tensile Properties of Natural HDPE Versus Recycle History (20 inch/min)**

<b>Recycle History</b>	<b>Break Stress PSI</b>	<b>Break Elongation Percent</b>	<b>Yield Stress PSI</b>	<b>Yield Elongation Percent</b>	<b>Initial Modulus PSI</b>
1	2187 (250)	46 (5)	4413 (54)	11.4 (0.8)	111300 (4668)
2	2383 (199)	41 (6)	4518 (56)	11.3 (0.6)	113800 (5043)
4	2538 (118)	36 (5)	4570 (64)	11.3 (0.8)	116100 (4898)
8	2529 (77)	33 (4)	4632 (34)	11.2 (0.5)	119000 (3685)
12	2380 (96)	31 (5)	4547 (32)	10.8 (0.7)	116100 (6605)

**Table 1-3. Tensile Properties of White HDPE Versus Recycle History (2 inch/min)**

<b>Recycle History</b>	<b>Break Stress PSI</b>	<b>Break Elongation Percent</b>	<b>Yield Stress PSI</b>	<b>Yield Elongation Percent</b>	<b>Initial Modulus PSI</b>
1	-----	-----	3850 (33)	12 (1)	123000 (8880)
2	-----	-----	3860 (39)	11 (0.9)	120000 (5600)
4	-----	-----	3920 (23)	12 (1.4)	122000 (10500)
8	-----	-----	4020 (35)	12 (0.4)	127000 (2340)
12	-----	-----	4090 (53)	12 (0.8)	123000 (9250)

**Table 1-4. Tensile Properties of White HDPE Versus Recycle History (20 inch/min)**

<b>Recycle History</b>	<b>Break Stress PSI</b>	<b>Break Elongation Percent</b>	<b>Yield Stress PSI</b>	<b>Yield Elongation Percent</b>	<b>Initial Modulus PSI</b>
1	2300 (185)	44 (9.5)	4420 (75)	10 (0.8)	125000 (5900)
2	2250 (196)	40 (4)	4400 (68)	12 (0.4)	115000 (3500)
4	2220 (63)	36 (6.4)	4450 (50)	11 (1.4)	117000 (8450)
8	2300 (320)	49 (13)	4500 (78)	12 (0.3)	114000 (3690)
12	2460 (140)	40 (15)	4600 (45)	11 (0.7)	122000 (6700)

**Table 1-5. Effect of Recycle History on the Notched Izod Impact Strength Away from Gate (ft-lbs/in)**

<b>Recycle History</b>	<b>Natural HDPE</b>	<b>White HDPE</b>
1	4.95	5.70
2	4.62	4.45
4	4.55	4.39
8	4.06	4.62
12	3.47	5.21

**Table 1-6. Effect of Recycle History on the Melt Index of Natural and White HDPE (g/10minutes at 2.16kg- 190°C)**

<b>Recycle History</b>	<b>Natural HDPE</b>	<b>White HDPE</b>
1	0.63	0.83
2	0.66	0.85
4	0.64	0.81
8	0.62	0.79
12	0.69	0.84

**Table 1-7. Color Test Results for Natural and White HDPE Versus Recycle History**

**Natural HDPE**

<b>Recycle History</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
1	69.20	-3.23	6.49	-----
2	67.49	-2.53	7.15	1.96
4	66.79	-2.50	7.77	2.82
8	65.96	-2.53	7.60	3.50
12	65.16	-2.40	7.81	4.33

**White HDPE**

<b>Recycle History</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
1	97.75	-0.35	2.02	-----
2	97.38	-0.32	2.03	0.38
4	97.08	-0.30	2.30	0.74
8	96.77	-0.27	2.53	1.11
12	96.36	-0.22	3.02	1.72

## **2. Study 2: A Study on the Pigmentability of Natural, Mixed Color, and White HDPE**

### **2.1 Scope**

One of the concerns associated with reuse of white HDPE that is collected and reprocessed as a separate material stream (i.e., a 100 percent white HDPE stream) is its pigmentability for nonwhite applications. It is relatively easy to pigment natural HDPE homopolymer bottle scrap using polyolefin-based color concentrates dry blended with the natural postconsumer HDPE homopolymer prior to the molding or extrusion processing operation. The white HDPE already contains a high concentration of white pigment ( $\text{TiO}_2$ ), which is very attractive for white applications (since no additional pigmentation is required); however, this additive will impact the pigmentability of the recycled flake for nonwhite applications. This study evaluates the pigmentability of white HDPE homopolymer; conventional, natural postconsumer HDPE homopolymer as a reference (control 1); and conventional mixed color postconsumer HDPE as a second reference (control 2).

### **2.2 Experimental Materials and Procedures**

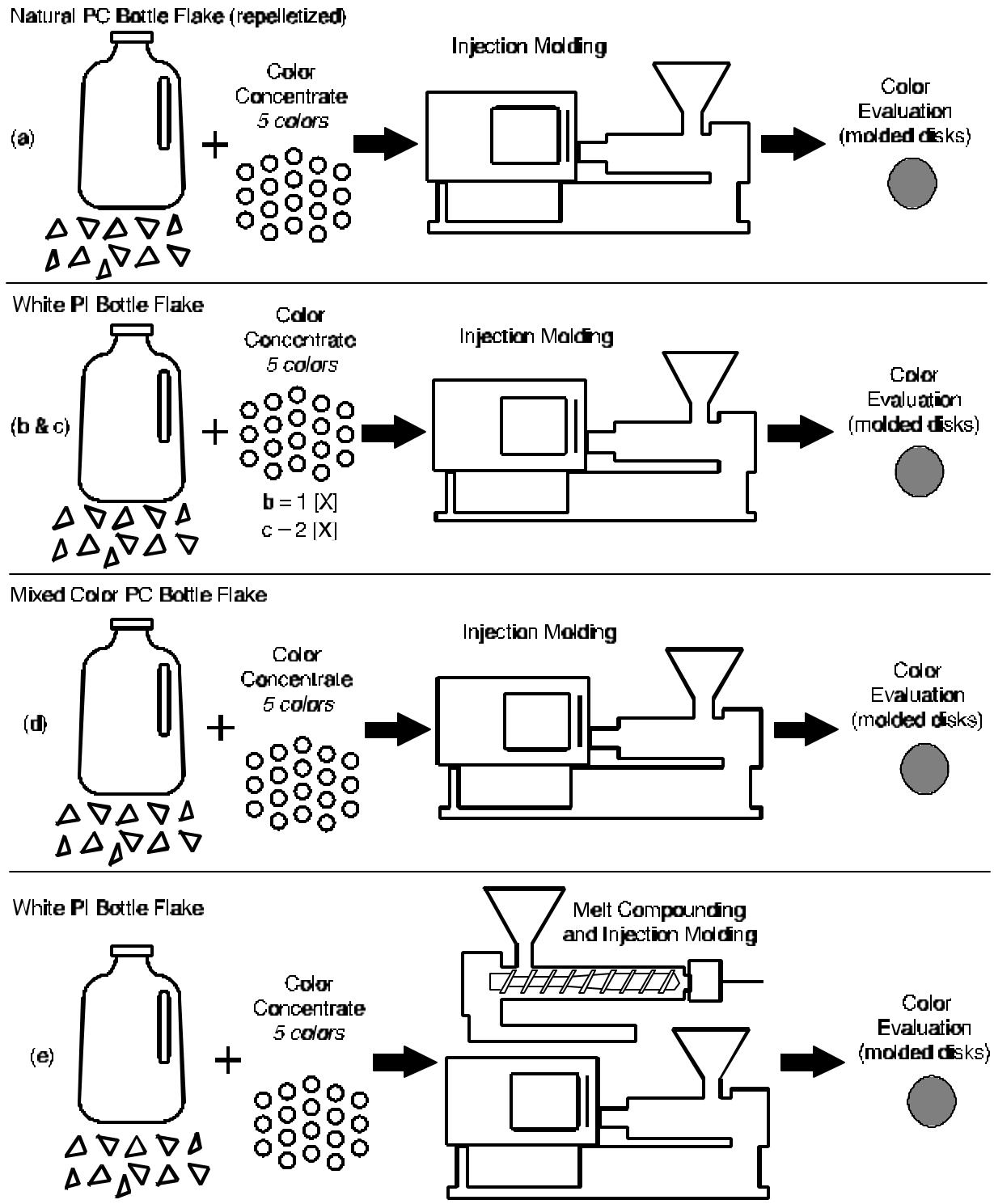
In this study, a series of five pelleted “representative/typical” color concentrates were used to pigment white HDPE bottle flake, natural HDPE bottle flake, and mixed color HDPE bottle flake. (The experimental procedures associated with Study 2 are depicted schematically in Figure 2-1.) These color concentrates were utilized at the appropriate concentrations recommended by the concentrate suppliers. The color concentrates used were green, blue, pink, orange, and brown, along with no pigment as a control.

The HDPE materials utilized for the study were:

- Clean, natural HDPE homopolymer postconsumer repelletized bottle flake (as described in Study 1).
- Clean, white HDPE homopolymer postindustrial flake (as described in Study 1).
- Clean, mixed color HDPE postconsumer bottle flake<sup>2</sup> (supplied by EnviroPlastics Corporation, Auburn, Massachusetts). The mixed color HDPE contains reground HDPE bottle flakes of various colors and different HDPE types. It is likely that the majority of the base resin is fractional melt index HDPE copolymer (typically used for household chemical containers such as detergent bottles) with lesser concentrations of pigmented or natural HDPE homopolymer.

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<sup>2</sup>It should be noted that since the mixed color HDPE is actually a mix of many separate reground postconsumer products, the material is by nature variable in composition.



**Figure 2-1.** In Study 2, the individual pigmentation of natural, white, and mixed color HDPE recycle streams is evaluated by incorporating various color concentrates with each type of HDPE.

The color concentrates were first dry blended with the three recycled HDPE materials listed above (illustrated in parts (a), (b), and (d) of Figure 2-1). The dry blending was performed at the recommended let-down ratios or concentrations by mixing in a V-shell blender for a period of 15 minutes. After dry blending with the base resins, the formulations were injection molded (using the equipment described in Study 1) to produce 75 mm diameter by 3.2 mm thick disk-shaped samples for color evaluation. Additional back pressure was added during injection molding to enhance mixing for all formulations. This is the typical processing methodology that plastic product manufacturers use to pigment their products.

Two additional pigmentation trials were conducted for only the white HDPE flake (illustrated in parts (c) and (e) of Figure 2-1). In one trial, two times the normal pigment concentration was added to the white HDPE in an effort to determine if higher pigment concentrations would result in significant improvements in color intensity (with an added economic penalty). In another trial, the white HDPE and color concentrate was first dry blended with the white HDPE and then melt compounded prior to injection molding in an effort to enhance the dispersion of the pigment concentrate within the HDPE. This additional melt compounding step was conducted using a single-screw pelletizing extruder similar to that described in Study 1. The melt blended pellets were then injection molded as described above.

After injection molding, all of the test samples (disks) were inspected visually and evaluated using a spectrophotometer as described in Study 1 to obtain the Hunter color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) and the color difference values ( $\Delta E^*$  values). The mean of six replicate measurements is reported.

### **2.3 Results**

The results of the color testing for Study 2, presented in Table 2-1, indicate the natural HDPE homopolymer was by far the easiest HDPE to pigment using the color concentrates, resulting in deep, well-dispersed colors. (Tables for Study 2 are presented on page 17.) No particular dispersion problems were observed with the natural HDPE, and the overall appearance of the colored natural samples was very good. The surface gloss was not particularly uniform due to the high viscosity of the blow molding grade (fractional melt index) HDPE, which is not normally used for injection molding. This is to be expected. The pigmentability of the natural HDPE samples could be described as excellent and these color values and sample appearances are used as the control for this study. The appearance of the pigmented samples produced from white HDPE and mixed color HDPE was then compared to the pigmented natural HDPE control.

Compared to the natural HDPE formulations, the white HDPE formulations (containing the normal/recommended color concentration) were significantly lighter in color. The  $+L^*$  values for the white HDPE formulations were very high (typically greater than 50), indicating the strong presence of whiteness. The  $\Delta E^*$  values in each case were more than 20 units greater than the natural HDPE control formulations. Colored samples produced from the white HDPE had a pastel appearance, rather than the deep, richer appearance obtained with the natural HDPE. When twice the normal pigment concentration was used with the white HDPE base resin, the colors did deepen, as indicated by the decrease in the  $+L^*$  value (less white) and the decrease in the  $\Delta E^*$  values (the difference in color relative to the control decreases, but is still very

significant). The added cost of the additional pigment concentrate (and the effect on physical properties) would likely limit such a practice in a production environment.

The most significant pigmentation problem associated with repigmenting the white HDPE (with another color) was the colorant dispersion. Unlike the translucent natural HDPE (where the eye can see into the depth of the sample for some distance), the white HDPE base resin is a very opaque material. One can only observe the surface layer of the sample and any color dispersion problems become visibly apparent. The very high melt viscosity (low melt index) of these blow molding-produced HDPEs makes color dispersion difficult. In addition, the mixing capability of a typical injection molding machine equipped with a general purpose plastication screw (such as that used in this study) is not particularly good. When the color concentrates were melt blended with the white HDPE prior to injection molding (as opposed to simple dry blending), the color dispersion problem was completely eliminated. While the melt-blended colored samples still had a pastel appearance, the color was evenly dispersed. The added cost of such a melt blending step is significant and may not be appropriate for many applications. The study does, however, point out the importance of sufficient melt mixing when repigmenting the white HDPE. Plasticating screws with enhanced mixing capability (or static mixers) would be recommended for when color concentrates are simply dry blended with white HDPE prior to injection molding.

While the primary purpose of this study was to compare the pigmentability of the white HDPE to that of natural HDPE (assuming the two materials are treated as separate recycling streams), the pigmentability of mixed color HDPE also was evaluated. In general, the mixed color material, initially a grayish - green, remained dark in color, even when the lighter color pigments were added. In most cases, the final color showed very little correlation with the color of the pigment concentrate added, especially in the case of lighter color pigments. Better results were obtained when the darker (green or brown) pigments were used. Pigment dispersion problems also were observed when the pigments were added to mixed color HDPE.

## **2.4 Conclusions**

If it is assumed that the natural HDPE and white HDPE are treated as separate material streams, then it can be concluded that the pigmentability of the natural HDPE is superior to that of the white HDPE. A wide variety of deep, well-dispersed colors can be obtained when color concentrates are dry blended and processed with the natural HDPE. When the pigments are added to the white HDPE (for nonwhite applications), the resulting colors are less deep, and more pastel, compared with the pigmented natural HDPE formulations. The most significant problem associated with adding pigments to the white HDPE was the uniformity of color dispersion, indicating the importance of using enhanced melt mixing (e.g., using mixing screws or static mixers) when repigmenting the white HDPE.

**Table 2-1. Comparison of Pigmentability of Natural, Mixed Color, and White HDPE**

**Green Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
Natural HDPE	28.80	-14.65	9.34	-----
Mixed color HDPE	46.13	-6.33	5.59	19.6
White HDPE	69.05	-10.82	1.62	41.2
White HDPE x2	60.15	-12.62	2.28	32.2

**Blue Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
Natural HDPE	29.36	-5.31	-31.01	-----
Mixed color HDPE	40.34	-13.30	-14.68	21.30
White HDPE	62.54	-15.50	-29.89	34.80
White HDPE x2	56.33	-14.95	-32.86	28.80

**Pink Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
Natural HDPE	41.45	47.49	-13.32	-----
Mixed color HDPE	51.27	4.97	4.29	47.10
White HDPE	85.72	26.02	-7.81	49.50
White HDPE x2	77.69	39.75	-11.16	37.40

**Orange Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
Natural HDPE	15.39	52.94	58.28	-----
Mixed color HDPE	46.48	31.32	33.64	33.00
White HDPE	63.00	47.46	40.71	22.50
White HDPE x2	60.68	50.35	44.22	17.70

**Brown Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
Natural HDPE	25.29	12.11	18.25	-----
Mixed color HDPE	35.27	10.80	18.07	10.10
White HDPE	48.66	13.74	20.36	23.50
White HDPE x2	42.31	14.10	19.03	17.20

### **3. Study 3: The Effect of White HDPE Homopolymer Bottle Flake on the Properties of Natural HDPE Homopolymer Bottle Flake**

#### **3.1 Scope**

The purpose of this study is to determine how white HDPE homopolymer bottle flake influences the physical properties of natural HDPE homopolymer flake. The need for this study is based on the concept that it may be possible to commingle the white and natural HDPE homopolymer waste streams as one recycling option for the white HDPE milk bottle.

#### **3.2 Experimental Materials and Procedures**

The materials utilized in this experimental study are the same as those used in Study 1:

- Natural HDPE homopolymer bottle flake (clean, repelletized postconsumer flake).
- White HDPE homopolymer postindustrial flake.

The white HDPE homopolymer was melt blended with the natural postconsumer pellets at concentrations of 0 (the control formulation), 5, 10, 20, and 50 percent white HDPE. The formulation concentrations are based on weight percentages. The formulations were first dry blended in a V-shell blender, then melt compounded using the 2 ½ inch 26:1 L/D single-screw pelletizing extruder described in Study 1. After melt compounding, the HDPE blends were injection molded into standard ASTM test specimens, as described in Study 1. The process is depicted schematically in Figure 3-1.

The physical property tests conducted in this portion of the study include:

- Tensile Properties (ASTM D638 at 2 and 20 inches per minute).
- Izod Impact Resistance (notched ASTM D256 - away from gate).
- Color Measurement (visual observation and spectrophotometer testing).

#### **3.3 Results**

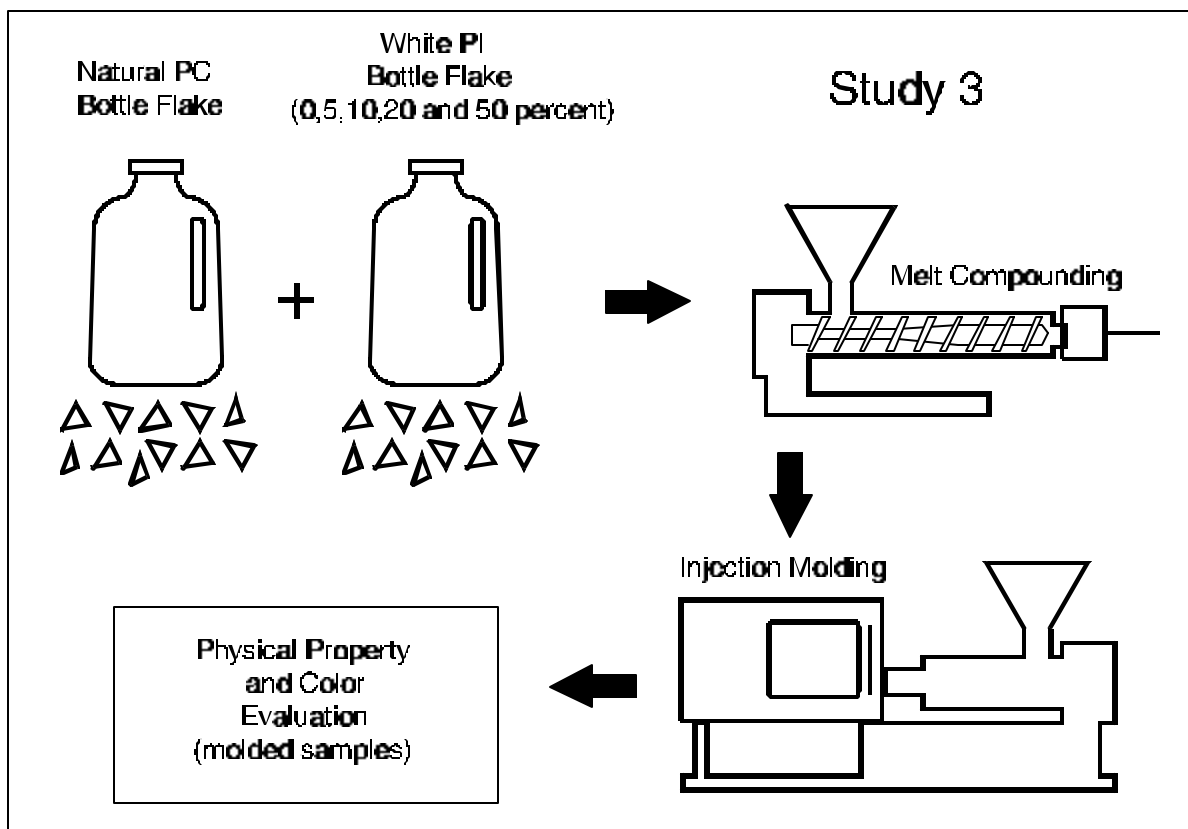
The physical property test results for the natural HDPE and white HDPE homopolymer blend study are given in Tables 3-1 through 3-4. (Tables for Study 3 begin on page 20.) In general, adding percentages of the white HDPE homopolymer to the natural HDPE homopolymer had little effect on the mechanical properties of the natural HDPE (at the concentrations evaluated). This is not a particularly surprising outcome, since both materials are very similar in composition (i.e., fractional melt index rate HDPE homopolymer). The difference is simply the addition of the TiO<sub>2</sub> in the case of the white HDPE. The tensile properties given in Tables 3-1 and 3-2, for example, show that the tensile strength, tensile elongation, and tensile modulus (rigidity) values of the natural HDPE are essentially unaffected by the presence of the white HDPE.

A regression analysis of the tensile yield strength values in Table 3-1 indicates that the strength of the natural HDPE is not significantly affected by the addition of the white HDPE. For tensile yield strength versus white HDPE concentration, the slope of the linear regression curve fit

changes by only +1.7 psi for each 1 percent of white HDPE added. This change is almost insignificant based on the intercept value of 3760 psi at 0 percent white HDPE (the control). There is some evidence of a small increase in rigidity with increasing white HDPE concentration; however, most of the experimental data falls within the error typically encountered when conducting mechanical property tests on recycled plastics.

The results of the Izod impact resistance tests are presented in Table 3-3. The Izod impact resistance of the natural HDPE homopolymer tended to improve slightly when the white HDPE homopolymer was added. This is possibly because the white HDPE homopolymer used in this study was postindustrial, while the natural HDPE homopolymer was postconsumer, which is likely to have a higher level of contamination. As stated previously, the impact performance of a thermoplastic is highly dependent upon contamination level. In any case, the addition of the white HDPE to the natural HDPE did not have a significant effect on the impact characteristics of the blends.

The most significant effect associated with blending white HDPE homopolymer with the natural HDPE homopolymer is the “whitening” of the formulation. The color test results given in Table 3-4 quantify this effect. The 95 percent natural HDPE and 5 percent white HDPE sample



**Figure 5-1.** In Study 3, the physical properties of natural HDPE homopolymer and white HDPE homopolymer blends are evaluated at white HDPE concentrations ranging from 0 to 50 percent. The purpose of the study is to simulate the commingled recycling of these two HDPE homopolymer streams.

maintains much of the light greenish translucent appearance of the 100 percent natural HDPE homopolymer. Even at this relatively low white HDPE concentration, however, an overall color shift ( $\Delta E^*$ ) value of 19.0 is observed relative to the natural material. As the white HDPE concentration increases, the whiteness (+L\*) and opacity of the formulation increases. The addition of the white HDPE to the natural HDPE whitens the formulation to a degree that is concentration dependent and is likely to have an impact on the pigmentability of the commingled blend. (The pigmentability of these white HDPE and natural HDPE blends was evaluated separately and is reported in Study 5.)

### 3.4 Conclusions

If natural HDPE homopolymer and white HDPE homopolymer bottle flake are treated as a commingled recycling stream, then it can be concluded that the mechanical performance of the natural HDPE is essentially unaffected by the addition of the white HDPE at white HDPE concentrations less than 50 percent (the limit of the study). The most significant effect of adding the white HDPE to the natural stream is the effect on the color of the blend. The degree of opacity and whiteness level is dependent upon the concentration of white HDPE added to the formulation.

**Table 3-1. Tensile Properties of Natural HDPE and White HDPE Blends (2 inch/minute)\***

	<b>Tensile Break Strength (psi)</b>	<b>Tensile Break Elongation Percent</b>	<b>Tensile Yield Strength (psi)</b>	<b>Tensile Yield Elongation Percent</b>	<b>Initial Tangent Modulus (psi)</b>
100N/0W	-----	-----	3713 (76)	10.7 (0.7)	115300 (24824)
95N/5W	-----	-----	3804 (39)	10.7 (0.2)	121700 (1735)
90N/10W	-----	-----	3763 (53)	11.8 (0.4)	122900 (2452)
80N/20W	-----	-----	3842 (33)	11.3 (0.8)	124400 (1382)
50N/50W	-----	-----	3826 (21)	11.3 (0.9)	126200 (6627)

\*Standard deviation shown in parentheses

**Table 3-2. Tensile Properties of Natural HDPE and White HDPE Blends (20 inch/minute)**

	<b>Tensile Break Strength (psi)</b>	<b>Tensile Break Elongation Percent</b>	<b>Tensile Yield Strength (psi)</b>	<b>Tensile Yield Elongation Percent</b>	<b>Initial Tangent Modulus (psi)</b>
100N/0W	2331 (97)	30.8 (2.0)	4255 (65)	10.6 (1.0)	123700 (6766)
95N/5W	2225 (213)	41.2 (9.4)	4320 (31)	11.1 (1.2)	121800 (5747)
90N/10W	2230 (318)	40.8 (9.4)	4300 (41)	11.3 (1.0)	116900 (5406)
80N/20W	2193 (194)	39.8 (6.0)	4304 (51)	11.5 (0.5)	118200 (4631)
50N/50W	2337 (135)	37.6 (8.0)	4294 (32)	10.2 (1.0)	120200 (5182)

**Table 3-3. Izod Impact Strength of Natural HDPE and White HDPE Blends**

	<b>Izod Impact Strength (ft-lb/in)</b>
100N/0W	6.3 (0.9)
95N/5W	7.7 (0.9)
90N/10W	8.2 (1.5)
80N/20W	8.1 (1.5)
50N/50W	8.0 (1.6)

**Table 3-4. Color Test Results for Natural HDPE and White HDPE Blends**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100N/0W	57.99	-4.22	2.52	-----
95N/5W	76.97	-3.30	2.73	19.00
90N/10W	80.81	-2.45	3.39	22.90
80N/20W	79.66	-1.91	3.18	21.80
50N/50W	92.24	-1.27	2.45	34.50

## **4. Study 4: The Effect of White HDPE Homopolymer Bottle Flake on the Properties of Mixed Color HDPE Bottle Flake**

### **4.1 Scope**

The purpose of this study is to determine how white HDPE homopolymer bottle flake influences the physical properties of mixed color HDPE flake (a postconsumer mix of pigmented copolymer and homopolymer). Like the previous study, the need for this study is based on the concept that it may be appropriate to commingle the white HDPE homopolymer and mixed color HDPE waste streams, as a recycling option for white pigmented milk bottles. This often is described as the most likely recycling scenario for pigmented HDPE milk bottles. In practice, this recycling option may present performance or compatibility problems for the mixed color material, since much of the mixed color bottle stream is based on the somewhat more flexible (less crystalline), more chemically resistant HDPE copolymer.

### **4.2 Experimental Materials and Procedures**

The base material utilized in this experimental study was clean, mixed color postconsumer HDPE bottle flake (supplied by EnviroPlastics Corporation, Auburn, Massachusetts). The mixed color HDPE contains reground HDPE bottle flakes of various color, and different HDPE types. As stated in Study 2, it is likely that the majority of the base resin is fractional melt index HDPE copolymer (typically used for household chemical containers such as detergent bottles) with lesser concentrations of pigmented or natural HDPE homopolymer. The white HDPE homopolymer postindustrial bottle flake is the same as that described in previous studies in this report.

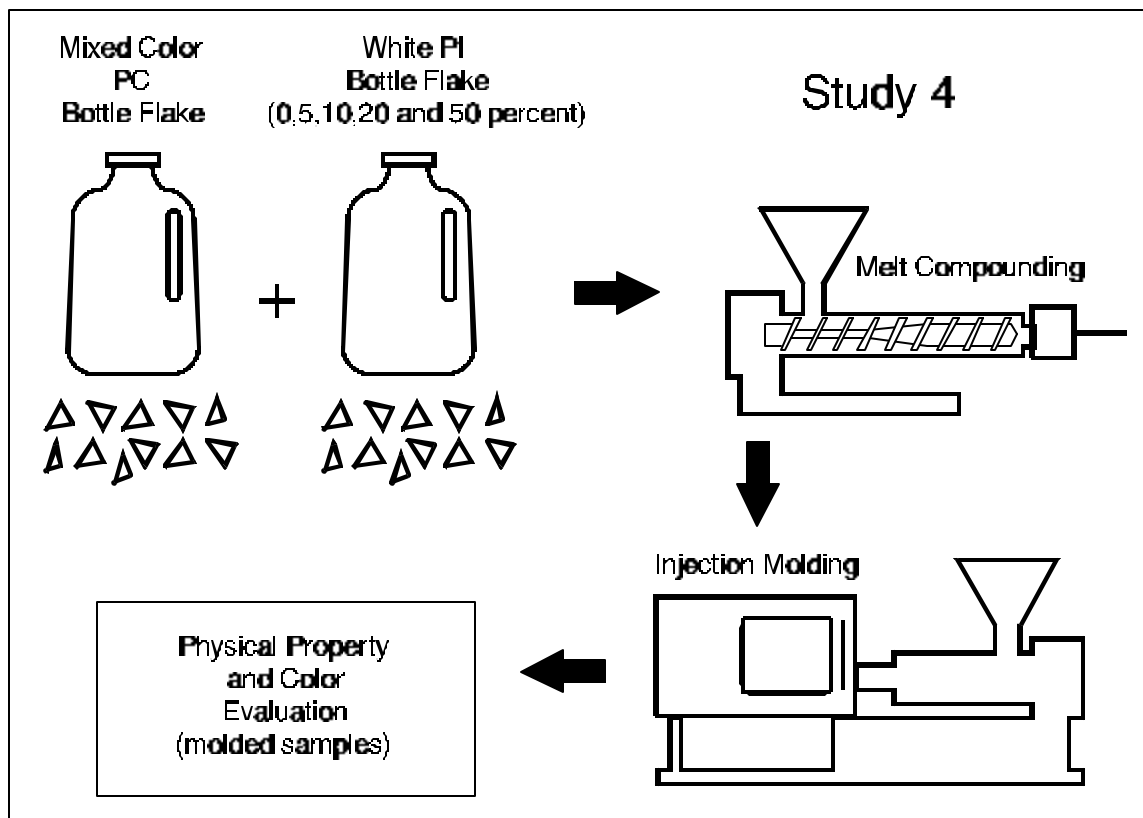
The white HDPE homopolymer was melt blended with the mixed color postconsumer flake at concentrations of 0 (the control formulation), 5, 10, 20, and 50 percent white HDPE. These formulation concentrations are based on weight percentages. As in Study 3, the formulations were first dry blended in a V-shell blender, then melt compounded using the 2 ½ inch 26:1 L/D single-screw pelletizing extruder described in Study 1. After melt compounding, the HDPE blends were injection molded into standard ASTM test specimens, as described in Study 1. This process is depicted in Figure 4-1.

The physical property tests conducted in this portion of the study include:

- Tensile Properties (ASTM D638 at 2 and 20 inches per minute).
- Izod Impact Resistance (notched ASTM D256 - away from gate).
- Color Measurement (visual observation and spectrophotometer testing).
- Environmental Stress Crack Resistance (ASTM D1693).

### 4.3 Results

The physical property test results for this study are given in Tables 4-1 through 4-4. (Tables for Study 4 begin on page 25.) Like Study 3, the purpose here is to simulate commingled recycling of white HDPE with an existing HDPE recycling stream, in this case the mixed color stream. In the previous study, white HDPE was blended with the natural homopolymer HDPE stream with little or no effect on mechanical performance. In this study, the white HDPE homopolymer is blended with the mixed color stream, resulting in a measurable but modest effect on some of the mechanical properties of the mixed color HDPE. The tensile property results given in Tables 4-1 and 4-2, for example, suggest that the mixed color HDPE does become somewhat more rigid (i.e., higher modulus) when the white HDPE homopolymer is added. The increase in modulus or rigidity is only 3 to 5 percent at white HDPE concentrations of 20 percent. Even at a 50 percent white HDPE concentration, the modulus increase is on the order of 10 percent or less. This tensile property data indicates that while these property changes are measurable, they are not extremely significant, particularly at white HDPE concentrations of 20 percent or less. All of the property changes are concentration dependent.



**Figure 6-1.** In Study 4, the physical properties of mixed color HDPE PC flake and white HDPE PE (homopolymer) blends are evaluated at white HDPE homopolymer concentrations ranging from 0 to 50 percent. The purpose of the study is to simulate the commingled recycling of these two HDPE recycle streams.

The Izod impact resistance data presented in Table 4-3 indicate there is a modest increase in the impact resistance of the mixed color formulation when the white HDPE is added to the mixed color HDPE. The increase is not extremely significant and, as stated earlier, may be attributed to the fact that the white HDPE was postindustrial rather than postconsumer material.

The addition of white HDPE homopolymer to mixed color HDPE also affected the color of the mixed color HDPE. The color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) and the color difference values ( $\Delta E^*$  values) given in Table 4-4 are relatively small at the 5 to 20 percent white HDPE concentration levels, but become more significant at the 50 percent white HDPE concentration. The addition of 5 percent white resulted in a whiteness increase ( $+L^*$ ) of only about 1.3, a measurable increase, but barely detectable by the naked eye. As the concentration of white HDPE increases, the characteristic mixed color HDPE, initially a grayish green, begins to take on a lighter gray appearance.

The last physical property evaluated for the white HDPE homopolymer and mixed color HDPE blends is their chemical resistance. Many household chemical containers are produced from pigmented HDPE copolymer (due to its enhanced stress cracking resistance). While enhanced chemical resistance is not a requirement for most mixed color postconsumer HDPE applications (secondary recycling), chemical resistance may be a factor in some recycling applications. Specifically, in this study, the Environmental Stress Crack Resistance of the HDPE blends (molded test bars) was evaluated in accordance with ASTM D1693. For this test, notched samples were subjected to a bending stress while immersed in an aggressive chemical (Igepal) at a temperature of 50°C using a temperature-controlled water circulating bath. Ten samples from each formulation were subjected to the chemical and the appearance of stress cracks was monitored as a function of time.

The results of this test procedure, presented in Table 4-5, show that the addition of white HDPE homopolymer to the mixed color HDPE appeared to alter the stress crack resistance of the mixed color HDPE only at the higher white HDPE homopolymer concentrations (i.e., 20 and 50 percent white HDPE). In all cases, there were no failures (cracks) after 5 hours of exposure to the reagent. Three of the formulations (including the control) showed one or two failures after 8 hours of exposure. After 24 hours of exposure, the formulation containing 20 percent white HDPE homopolymer had the greatest number (8) of failures (small but visually detectable cracks in the notch region of the samples). At that same time, the formulation containing 50 percent white HDPE homopolymer had only 5 failures; however, the mode of failure for this particular formulation (and only this formulation) was a more severe cracking, compared to the micro cracks for all of the other formulations. The formulations containing 5, 10 (and for the most part even 20 percent HDPE) showed very similar behavior to the control formulation produced from 100 percent mixed color HDPE.

#### **4.4 Conclusions**

If mixed color HDPE (a mix of pigmented copolymer and homopolymer flake) and white HDPE homopolymer bottle flake are treated as a commingled recycling stream, then it can be concluded that the mechanical performance of the mixed color HDPE is altered to a limited degree by the addition of the white HDPE homopolymer. The addition of white HDPE to the mixed color

formulation resulted in a somewhat stiffer, stronger, but less ductile formulation. Even at a white HDPE homopolymer concentration of 50 percent, however, the tensile property changes observed ranged from 5 to a maximum of 20 percent. The changes were much less significant at lower concentrations of white HDPE homopolymer. The impact resistance of the mixed color material was essentially unaffected by the addition of the white HDPE. The addition of the white HDPE resulted in only a moderate lightening of the characteristic grayish green mixed HDPE color. (The pigmentability of these blends was evaluated separately in Study 5.) The results of the environmental stress crack resistance tests suggest that the chemical resistance of the mixed color HDPE is reduced if higher concentrations (greater than 20 percent) white HDPE homopolymer are introduced.

**Table 4-1. Tensile Properties of Mixed Color HDPE and White HDPE Blends (2 inch/minute)\***

	<b>Tensile Break Strength (psi)</b>	<b>Tensile Break Elongation Percent</b>	<b>Tensile Yield Strength (psi)</b>	<b>Tensile Yield Elongation Percent</b>	<b>Initial Modulus (psi)</b>
100MC/0W	-----	-----	3370 (25)	13.1 (1.4)	98400 (2821)
95MC/5W	-----	-----	3363 (46)	13.1 (1.3)	97200 (1081)
90MC/10W	-----	-----	3388 (30)	12.0 (0.7)	101000 (4730)
80MC/20W	-----	-----	3396 (58)	12.9 (0.8)	101100 (2574)
50MC/50W	-----	-----	3492 (81)	11.9 (1.0)	110800 (4263)

\*Standard deviation shown in parentheses

**Table 4-2. Tensile Properties of Mixed Color HDPE and White HDPE Blends (20 inch/minute)**

	<b>Tensile Break Strength (psi)</b>	<b>Tensile Break Elongation Percent</b>	<b>Tensile Yield Strength (psi)</b>	<b>Tensile Yield Elongation Percent</b>	<b>Initial Modulus (psi)</b>
100MC/0W	2107 (222)	41.3 (6.4)	3767 (74)	12.2 (0.9)	96400 (5212)
95MC/5W	2163 (364)	35.6 (9.0)	3790 (37)	12.5 (1.5)	101500 (4123)
90MC/10W	1977 (163)	38.1 (2.0)	3887 (41)	12.6 (0.5)	98400 (3287)
80MC/20W	2057 (47)	36.3 (3.8)	3899 (51)	12.8 (1.3)	101000 (7992)
50MC/50W	2135 (226)	34.7 (4.9)	3972 (25)	11.6 (0.8)	104700 (7088)

**Table 4-3. Izod Impact Strength of Mixed Color HDPE and White HDPE Blends**

	<b>Izod Impact Strength (ft-lb/in)</b>
100MC/0W	3.3 (0.2)
95MC/5W	3.5 (0.3)
90MC/10W	3.9 (0.7)
80MC/20W	3.6 (0.4)
50MC/50W	4.2 (0.5)

**Table 4-4. Color Test Results for Mixed Color HDPE and White HDPE Blends**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100MC/0W	59.19	-2.05	6.29	-----
95MC/5W	60.48	-2.31	5.97	1.40
90MC/10W	61.49	-1.71	6.38	2.30
80MC/20W	63.90	-1.47	6.53	4.77
50MC/50W	73.33	-1.83	5.55	14.16

**Table 4-5. Environmental Stress Crack Resistance of Mixed Color and White HDPE Blends**

Time (hours)	Number of Sample Failures (10 samples total)				
	100MC	95MC/5W	90MC/10W	80MC/20W	50MC/50W
0.1	0	0	0	0	0
0.25	0	0	0	0	0
0.5	0	0	0	0	0
1	0	0	0	0	0
1.5	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
8	1	2	0	0	1
16	2	3	3	4	2
24	5	4	4	8	5*
32	6	6	8	9	8*
40	10	10	8	9	10*
48	10	10	10	10	10*

\*Indicates more severe cracking

## **5. Study 5: A Study on the Pigmentability of Natural and White HDPE Blends and Mixed Color and White HDPE Blends**

### **5.1 Scope**

The purpose of this study is to determine how white HDPE homopolymer bottle flake influences the pigmentability of natural HDPE homopolymer flake and mixed color HDPE bottle flake. This study is an extension of Studies 3 and 4, where the physical properties of the HDPE blends were evaluated. Here, the ability to pigment commingled natural and white HDPE blends and mixed color and white HDPE blends with color concentrates is evaluated.

### **5.2 Experimental Materials and Procedures**

The HDPE materials evaluated in this experimental study were:

- Natural HDPE homopolymer bottle flake (clean repelletized postconsumer flake).
- White HDPE homopolymer postindustrial flake.
- Mixed color HDPE (clean postconsumer flake).

In the first part of this study (Study 5a), the white HDPE homopolymer was melt blended with the natural postconsumer pellets at concentrations of 0 (the control formulation), 5, 10, and 20 percent white HDPE. The 20 percent white HDPE value was selected (versus 50%) as a more realistic upper (white HDPE) concentration limit for this color study, based on market figures. White milk bottles represent a relatively small fraction of the total milk bottle waste stream, which in turn represents only a fraction of the total natural HDPE bottle waste stream that includes water and juice containers. Once again, the formulation concentrations are based on weight percentages.

The formulations were first dry blended in a V-shell blender and then melt compounded using the 2 ½ inch 26:1 L/D single screw pelletizing extruder described in Study 1. After melt compounding, the natural and white HDPE blends were dry blended with color concentrates at the appropriate let-down ratios (concentrations). The colorants used in this study were formulated for use with HDPE. The colors used were standard product yellow, orange, red, green, brown, and black concentrate pellets supplied by Hudson Color Concentrates Inc., Hudson, New Hampshire. The colorants were dry blended with the natural and white HDPE blends prior to being injection molded into standard ASTM test specimens, as described in Study 1.

The process described above was then repeated in the second part of this study (Study 5b) using mixed color HDPE in place of the natural HDPE. The mixed color and white HDPE blends were compounded, pigmented, and injection molded in an equivalent manner. After molding, color measurements were conducted using a spectrophotometer/Hunter L\* - a\* - b\* color coordinate system with cool fluorescent light simulation. The processes used in this study are illustrated in Figure 5-1.

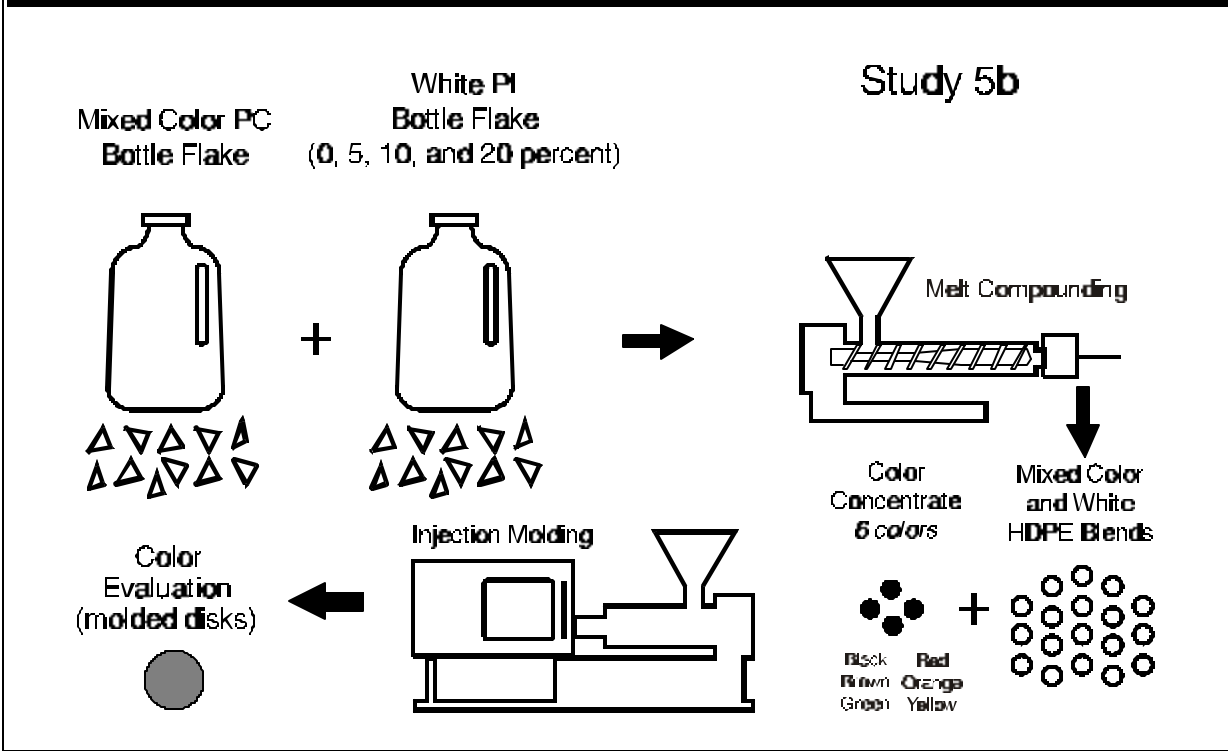
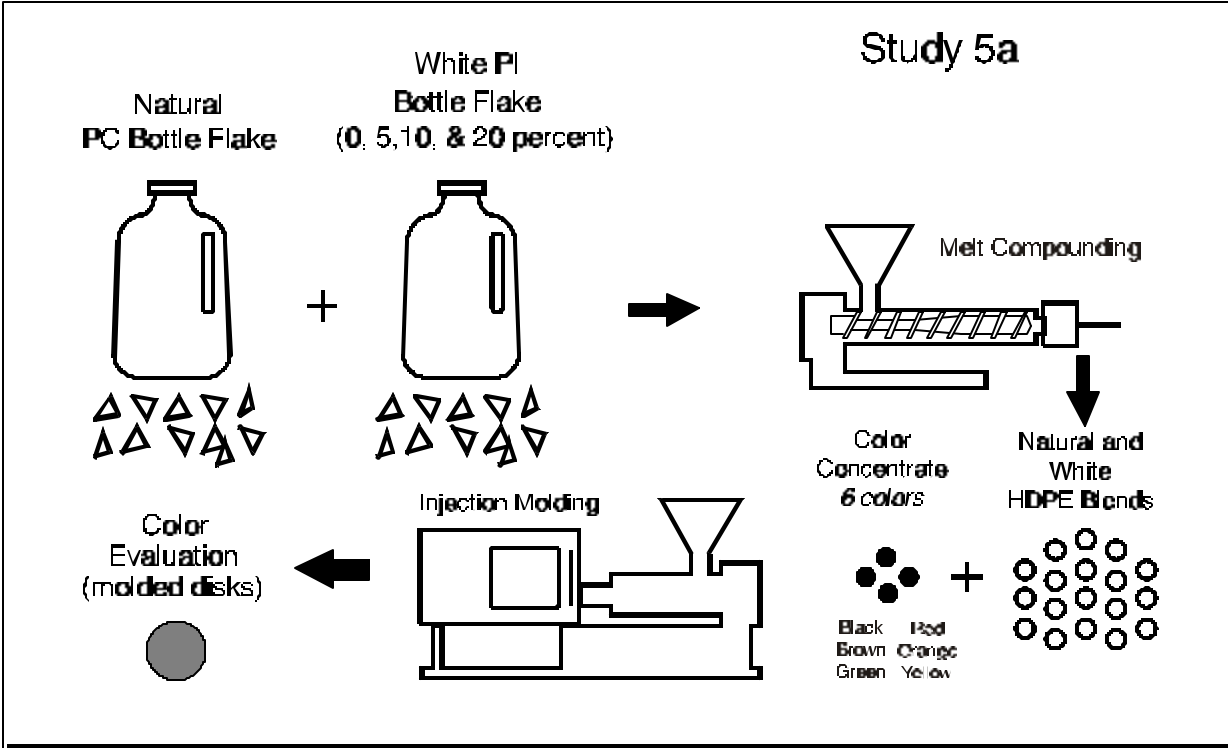


Figure 7-1. In Study 5, blends of natural and white HDPE were compounded and pigmented to determine the effect of white HDPE concentration on the pigmentability of the blend (5a). The procedure was repeated (in 5b) for blends of mixed color and white HDPE.

### 5.3 Results

The color testing results of the natural and white blends with pigment are given in Table 5-1. (Tables for Study 5 begin on page 31.) The pigmentability of the natural HDPE and white HDPE blends was on the whole relatively good. At a 5 percent white HDPE concentration, the color shifts were measurable, but relatively small. The changes in color for the black, brown, orange, and yellow samples were barely detectable with the naked eye. A lightening or whitening effect was more readily observable with the green and red pigments. At the 5 percent white HDPE concentration, the color dispersion was nearly equivalent to that of the natural (control) samples. At a 10 percent white concentration, the colors continued to lighten; however, the visual change was very small for most of the colors. The changes in the red and green samples were most visible. At the 10 percent white concentration, traces of color dispersion or nonuniform color begin to appear; however, the overall surface appearance is still relatively good for all samples except the red. At the 20 percent white HDPE concentration, a color dispersion problem becomes more significant as all of the samples (except the yellow) had a somewhat streaky, nonuniform appearance.

Color testing results of the mixed color HDPE and white HDPE blends are presented in Table 5-2. In general, the mixed color HDPE is difficult to pigment, as indicated in Study 2. The grayish green 100 percent mixed color HDPE (control) can be pigmented most easily with darker colors; however, the color uniformity is more of a problem than that of the natural material. In addition, when lighter color pigments are used, the resulting sample color can be very different from that of the color concentrate added to the formulation.

In general, the pigmentability of the mixed color material was not greatly affected by the addition of the white HDPE. This was particularly true for the lighter colors. The color changes were not extremely significant for almost all of the mixed color and white HDPE blends. The one notable exception to this was the set of samples produced with the black pigment. The black samples produced from the blends containing the higher white HDPE concentrations (10 and 20 percent) tended to have a nonuniform color with streaky regions of black and white.

### 5.4 Conclusions

In general, the pigmentability of blends produced from natural HDPE and white HDPE was not significantly affected by the presence of the white HDPE at white HDPE concentrations in the 5 to 10 percent range (with one exception). The color shifts were relatively small and difficult to detect visually at these concentrations of white HDPE. As the concentration of white HDPE reached 20 percent, a noticeable color shift is observed, and color dispersion starts to become a problem. At these white HDPE concentrations, the use of plasticating screws with enhanced mixing capability or static mixers would be recommended. The pigmentability of the mixed color HDPE and white HDPE were less sensitive to the presence of white HDPE. The color shifts were relatively small. There were more color dispersion problems, however, with the mixed color and white formulations (even with the 100 percent mixed color control samples). The presence of the white HDPE did not appear to aggravate the color dispersion problem for the mixed color and white HDPE blends, except for the samples containing the black pigment.

**Table 5-1. Color Test Results for Natural HDPE and White HDPE Blends Containing Color Concentrates**

**Black Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100N/0W	26.63	-0.06	-0.16	-----
95N/5W	27.19	-0.07	-0.85	0.89
90N/10W	28.23	-0.05	-1.39	2.00
80N/20W	29.15	-0.05	-2.09	3.18

**Brown Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100N/0W	40.19	10.43	14.27	-----
95N/5W	41.60	10.71	14.34	1.45
90N/10W	43.07	10.86	14.22	2.92
80N/20W	46.38	10.97	13.49	6.27

**Green Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100N/0W	51.30	-24.74	19.03	-----
95N/5W	54.02	-25.44	20.06	2.99
90N/10W	57.04	-25.49	21.50	6.30
80N/20W	57.66	-24.55	18.86	6.36

**Red Pigment**

<b>Material</b>	<b>L*</b>	<b>a*</b>	<b>b*</b>	<b>DE*</b>
100N/0W	42.51	27.47	7.51	-----
95N/5W	45.92	31.54	7.52	5.32
90N/10W	49.77	32.79	4.76	9.41
80N/20W	55.75	32.70	1.77	15.35

### Orange Pigment

Material	L*	a*	b*	DE*
100N/0W	52.79	28.39	49.70	-----
95N/5W	66.83	30.00	51.73	4.80
90N/10W	57.89	29.40	50.22	5.23
80N/20W	69.70	26.78	47.59	7.48

### Yellow Pigment

Material	L*	a*	b*	DE*
100N/0W	79.54	-1.52	71.62	-----
95N/5W	85.46	-0.60	77.06	8.08
90N/10W	86.27	-0.74	74.87	7.51
80N/20W	87.67	-1.13	70.98	8.16

**Table 5-2. Color Test Results for Mixed Color HDPE and White HDPE Blends Containing Color Concentrates**

### Black Pigment

Material	L*	a*	b*	DE*
100MC/0W	39.16	-0.37	-2.27	-----
95MC/5W	31.45	-0.10	-2.25	7.71
90MC/10W	31.57	-0.13	-2.42	7.60
80MC/20W	36.88	-0.23	-2.91	2.38

### Brown Pigment

Material	L*	a*	b*	DE*
100MC/0W	48.67	9.22	11.75	-----
95MC/5W	48.19	8.75	11.65	0.68
90MC/10W	45.18	9.86	12.84	3.71
80MC/20W	45.98	10.19	13.01	3.13

### Green Pigment

Material	L*	a*	b*	DE*
100MC/0W	57.76	-10.91	13.84	-----
95MC/5W	55.40	-15.10	14.08	4.82
90MC/10W	55.53	-14.92	14.45	4.63
80MC/20W	58.47	-12.55	13.76	1.83

### Red Pigment

Material	L*	a*	b*	DE*
100MC/0W	50.23	18.96	0.51	-----
95MC/5W	48.01	22.85	1.60	4.61
90MC/10W	49.24	19.80	0.95	1.37
80MC/20W	53.11	18.45	0.24	2.93

### Orange Pigment

Material	L*	a*	b*	DE*
100MC/0W	60.11	5.14	26.20	-----
95MC/5W	60.23	7.31	27.72	2.65
90MC/10W	59.96	8.69	26.24	3.55
80MC/20W	61.24	10.27	28.02	5.56

### Yellow Pigment

Material	L*	a*	b*	DE*
100MC/0W	63.46	-2.45	21.71	-----
95MC/5W	64.72	-2.57	26.33	4.79
90MC/10W	64.73	-2.50	32.27	10.64
80MC/20W	67.86	-2.89	31.83	11.05