THE USE OF RECYCLED POLYETHYLENE IN THE MANUFACTURING OF CORRUGATED DRAINAGE PIPE FOR ROADWAY APPLICATIONS

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Abstract: There is an interest in the United States to incorporate recycled polyethylene (PE) into resins used to make corrugated drainage pipe, in diameters up to 1.52 meters. Obviously, the long-term performance of pipe containing recycled PE is critical. Twenty-two different recycled PE resins were evaluated and compared. These included post-consumer and post-industrial, and regrind and reprocessed. Then, sixty-seven blends were prepared with virgin PE resins and the blends evaluated for short and long-term properties. The results have demonstrated that contamination control is the most important factor affecting durability and that blends containing up to 40% recycle content can be made with properties equal to or better than the virgin pipe resin. This paper will discuss the important aspects of the use of recycled PE and how certain properties vary with recycled content.

Keywords: drainage, durability, high density polyethylene, piping, stress crack, tensile strain.

INTRODUCTION

The corrugated drainage pipe market in the United States consumes in excess of a billion pounds of virgin high-density polyethylene (HDPE) annually. At the same time, millions of pounds of recyclable HDPE are generated each year. Industry-funded research has demonstrated the feasibility of blending recycled and virgin HDPE to manufacture corrugated drainage pipe. The working hypothesis is that good quality pipe can be manufactured from such blends if critical material properties that affect pipe performance and durability, such as strength and structural properties, density, melt index, environmental stress-crack resistance, and thermal stability, are consistently maintained at specified levels in the blends.

At present, the American Association of State Highway Officials (AASHTO) specifications do not permit the use of recycled HDPE in the production of corrugated drainage pipe. Research is needed to:

- Determine if there are blends of virgin and recycled HDPE that meet the current material property requirements specified by AASHTO and defined in ASTM D3350;
- Evaluate blends of virgin and recycled HDPE to assure that long-term stress-crack resistance and antioxidant effectiveness are equivalent to that of pipe made from virgin HDPE, as currently specified in AASHTO M294 or M252;
- Identify whether contaminants such as polypropylene and ethylene vinyl alcohol copolymer present in recycled HDPE will adversely affect the long-term service life of finished pipe, and;
- Develop specifications and test methods to support the use of recycled HDPE in the manufacture of corrugated drainage pipe.

This project was specifically developed to determine what kinds of recycled PE were available, what levels of contamination were present, and how recycled PE would perform when blended with virgin PE (Thomas 2006, 2008). The currently used corrugated pipe resins have densities from 0.948 to 0.955 g/cm^3, melt indexes of about 0.1-0.3 g/10 min, yield stress of around 27.6 MPa, and NCLS (ASTM F2136) failure times of more than 24 hrs.

Post-Industrial Recycled (PIR) Polyethylene

This is a large category that includes scrap from processes such as pipe, sheet, thermoforming, injection moulding, blown film, tubing and more. This includes low density, linear low density, linear medium density, and high density (homo- and co-polymer). The molecular weight also varies from injection moulding grade (low Mw, high MI) to thermoforming or blown film (high Mw, low MI).

There are certainly resins which would be appropriate for incorporation into pipe available from the post-industrial market. However, there is a downside. Post-industrial is sold mainly through brokerage firms, and is commonly sold on a lot-to-lot basis. This means that reliable and continuous waste streams are not commonly found. Additionally, it is often in a bulk form and/or comingled with different grades of PE. The result is that it is used mostly in non-critical applications by plastic processors whom have the capabilities to accommodate different grades of polyethylene.

Despite the limitations mentioned above, three PIR polyethylene samples were received for evaluation in this study. Two (HDPE and LDPE) were provided by a reprocesser that also manufacturers post-consumer polyethylene. The third (LMDPE) was regrind scrap from a manufacturer of geomembranes.

Post-Consumer Recycled (PCR) High Density Polyethylene

This is a smaller category, in terms of different types of resins, that includes primarily recycled bottles and high-strength shopping or trash bags. The volume of good recycled bags is low because the bulk density (volume/weight ratio) is low and the high quality bags are usually contaminated with lower quality LDPE bags. Additionally, the volume of plastic bags is shrinking because their use is being legislated against in a growing number of communities throughout the United States.

The bottles can either be natural or coloured. The natural bottles are most often the ½ to 1 gallon water, juice, or milk jugs. They are made from HDPE homopolymer, which is a resin with high strength and poor stress crack resistance.

The coloured bottles include those for liquid detergent, cleaners, shampoos, fabric softeners, and others marked with an international number 02 recycling code. The resin used in coloured bottles is a HDPE co-polymer which is not as strong as the homopolymer but has better cracking resistance.

Both the natural (NAT) and mixed coloured (MC) HDPE resins are available as regrind (chips) or reprocessed (pellets). The reprocessed pellets have the advantage of being melt-filtered during the pelletizing process. This is essentially one additional purification step. The coloured bottle recycled resin contains a significant amount of natural bottles in it. There is an increasing number of recyclers who are hand-separating the natural bottles from the mixed coloured bottles because the natural resin has significantly higher value on the recycled resin market. The difference can be $0.10 per pound, or more.

Most of the samples found during this study came through contact with the Association of Postconsumer Plastic Recyclers (APR).

Nineteen samples of PCR-HDPE were received from six member companies of the APR and 2 non-members. The samples included natural regrind (1), natural reprocessed (3), mixed colour regrind (5), mixed coloured reprocessed (7), and 3 special blends project personnel are calling mixed colour plus. Two of these are mixed colour reprocessed with added high molecular weight HDPE to assist with processing, and improve properties such as impact strength and stress crack resistance. The third is a blend of mixed colour post-consumer with post-industrial.

Contamination

The types of foreign matter that may be found in post-consumer recycled HDPE include labels, paper, cardboard, dirt, aluminium foil, adhesives, and other polymers like PP (from caps), EVOH (barrier layers), PET or PVC. The recycled HDPE may be contaminated with other grades of PE, like LDPE which could affect the cracking resistance. Finally, there may be milk and detergent residue, which produce smoke and odours during processing (Scheirs 1998).

This study looked at the effects of particulates by adding known amounts of angular sand to virgin resins to see the effects on the properties, and also by performing melt filtration at different levels. The effects of EVOH were reduced through the use of a commercial compatibilizer. And, the effects of polypropylene were evaluated by looking at the effects of 2, 5, and 10% PP on some mechanical properties.

Virgin Resins for Blending

Three virgin resins that were AASHTO approved and certified by the Plastic Pipe Institute (PPI) were selected as representatives of typical pipe resins. Additionally, one linear low density polyethylene (LLDPE) and one medium density polyethylene (MDPE) were chosen to enhance the properties of the recycled materials during blending.

Blends of Recycled with Virgin PE

A total of 67 blends were prepared during this study. The resins used to make the blends are shown in Table 1 and the types of blends shown in Table 2.

Table 1. Resins used for blending

Resin	Abbreviation	Description
Virgin Resin 1	VR1	PPI certified AASHTO HDPE pipe resin.
Virgin Resin 2	VR2	PPI certified AASHTO HDPE pipe resin.
Virgin Resin 3	VR3	PPI certified AASHTO HDPE pipe resin.
Virgin LLDPE	LLDPE	Commercial linear low density polyethylene resin from a supplier that makes AASHTO pipe resin.
Virgin LMDPE	MDPE	Commercial linear medium density polyethylene resin from a supplier that makes AASHTO pipe resin.
Mixed Colour PCR 1	MCR1	Mixed-colour post-consumer reprocessed HDPE pellets composed of coloured and natural bottles.
Mixed Colour PCR 2	MCRG	Mixed-colour post-consumer regrind HDPE chips composed of coloured and natural bottle.
Natural PCR	NAT	Post consumer reprocessed HDPE pellets made from milk, juice, and water bottles.
Natural PCR + 10% LLDPE	N10LL	Blend of NAT with 10% LLDPE
Natural PCR + 35% MDPE	N35LL	Blend of NAT with 35% LLDPE
PIR High Density	PIR-HD	Blend of PCR high density bottles with PIR polyethylene.
PIR Medium Density	PIR-MD	Post industrial linear medium density polyethylene regrind chips from the sheet market.
PIR Low Density	PIR-LD	Post industrial low density polyethylene reprocessed pellets believed to contain mostly film and bags.

Table 2. Blends

Component A	Component B	Component C	Percentage Recycled	No. of Blends
VR1 or VR1 or VR3	MCR1 or MCRG		20,40,60,80 %	16
MCRG	MDPE		20,40,60,80 % 25,50,75 %	7
MCRG	PIR-MD		20,50,75 % PIR-MD*	3
75% MCR1	25% PIR-HD		100 %	1
50% VR3	25% MCR1	25% MDPE	25 %	1
VR2	NAT		20,40,60,80 %	4
NAT	LLDPE		5,10,20,40 %	4
NAT	MDPE		20,40,60,80 % 50 %	5
VR1 or VR2	N10LL		18,36,54,72 %	8
VR1	N35LL		7,14,21,28 %	4
65% NAT	35% PIR-LD		100 %	1
50% VR3	25% NAT	25% MDPE	25 %	1
VR1 or VR2 or VR3	PIR-HD		20,40,60,80 %	12

* These blends were 100% recycled

EXPERIMENTAL

Melt Blending by Extrusion

All blending and extruding were performed on a laboratory line consisting of a Welding Engineers Model HT8-222-2251 Twin Screw Extruder, a custom-built cooling bath equipped with a chiller and circulator and a Berlyn Corporation Model HV1 Pellitizer. The extruder has counter-rotating screws at a L:D ratio of 24:1. The extruder temperatures were set at 115 °C for the feed zone, and 177 °C for the mixing and metering zones. The die temperature was also 177 °C. The die was a single 6.35 mm diameter rod and the die was fitted with two, 25.4 mm diameter melt filter screen holders. All samples for extrusion were dry blended then gravity fed. The batch size was typically 1Kg. The screw speed was set at 220 rpm, which produced an output rate of about 6.8 Kg/hr (15 lb/hr). The residence time in the extruder was about 45 seconds. Samples of recycled regrind chips were melt blended twice and recycled reprocessed pellets were melt blended once. All the experimental blends were melt blended three times to ensure optimum blending. Virgin resins were also blended in the same manner to duplicate the heat history of the blends.

Plaque Preparation

Sample plaques were prepared according to ASTM D4703, *Practice for Compression Molding Thermoplastic Materials into Test Specimens, Plaques, or Sheets* on a Pasadena Hydraulic Industries Model P215H Platen Press. Two sizes of plaques were prepared. The plaque used for the BAM test specimens was 15.24 cm x 15.24 cm x 1.27 mm. The plaque used for all other tests was 17.78 cm x 17.78 cm x 1.9 mm. The smaller mould used 40g of pellets while the larger one used 65g.

The open cavity mould was charged with pellets in between two Mylar release sheets and placed in the press, which was pre-heated to 190°C. Once the mould reached 160°C, the set-point temperature was reduced to 177°C and the mould quickly pressed to 20.68 MPa. After the plastic was allowed to relax for at least 5 minutes, the mould temperature was recorded and the cooling process begun. The mould temperature was lowered by slowly opening a needle valve, allowing cooling water to enter the platens. The temperature was recorded every 30 seconds and the cooling was done at a rate of 15 ± 2°C. Once the temperature was below 45 °C, the mould was removed.

Properties Measured

The recycled resins obtained and the blends made from them were both subjected to extensive testing. The tests performed along with the standard test methods used are shown in Table 1. Properties measured by non-standardized, “custom”, methods will be described below. Every test was not performed on every sample.

The % Volatiles were determined on duplicate 2g samples, in aluminium pans, heated to 175° C for 1 hour. This test was only performed on the as-received recycled resins.

The % Polypropylene (PP) was determined by differential scanning calorimetry (DSC). A 3-6 mg specimen was heated at 10° C/min in nitrogen from room temperature to 200° C. The heat of fusion of the polypropylene portion of the curve was determine and the % PP was calculated from the known heat of fusion of PP minus a correction for the overlap between the end of the HDPE melt and the beginning of the PP melt.

Table 1. Properties measured

Property	ASTM Test Method
Density	D1505
Melt Flow Rate	D1238
% Volatiles	--
% Colour + Ash	D4218
% Ash	D5630
% Polypropylene	--
Yield Stress	D638
Break Strain	D638
15% NCTL	D5397
BAM Stress Crack	--
Oxidative Induction Time	D3895

The BAM Stress Crack Test has been around for nearly 15 years but has never been standardized. This test was introduced by researchers in Germany at the Bundesanstalt für Materialforschung und-prüfung (BAM). It was developed for evaluating textured coatings for Geomembranes. It was used successfully on both textured Geomembranes and heat-bonded seams (Thomas and Woods-DeShepper 1993, Thomas, *et al*. 1995). The test was performed on 12.7 mm wide by 15.24 cm long specimens, about 1-1.2 mm thick. The specimens were mounted on a stress crack frame, placed in a 5% Igepal CA-720 aqueous solution at 80° C, and put under a tensile stress of 4 MPa. The specimens stayed in the bath until they broke or until 300 hours had elapsed. The main difference between this test and ASTM D5397 is that no notch is used. A stress crack will grow where ever there is a critically sized defect (Wu, et al. 2000). The test is sensitive to the basic stress crack resistance of the resin and the defects in the specimens.

RESULTS

Recycled Polyethylene Resins

There were a total of 22 different recycled resins obtained from 9 different companies. A breakdown of the samples is shown in Table 2.

Table 2. Recycled PE samples obtained for evaluation and blending

Resin Type	Description	Number of Samples	Physical Form
Post-Industrial (PIR)	High Density (HD)	1	Reprocessed pellets
	Medium Density (MD)	1	Regrind chips (flake)
	Low Density (LD)	1	Reprocessed pellets
Post- Consumer (PCR)	Natural Bottles (NAT)	1	Regrind chips (flake)
		3	Reprocessed pellets
	Mixed Color Bottles (MC)	5	Regrind chips (flake)
		10	Reprocessed pellets

A summary of some of the important properties is shown in Table 3. The table does not distinguish between regrind or reprocessed because all regrind samples were run twice through the twin screw extruder and pelletized and the reprocessed was melt blended and pelletized once.

The value of the density of recycled resins is highly questionable. Theoretically, the yield stress and the density are linearly related. In fact, a relationship has been derived from a series of data presented by the Plastic Pipe Institute (Plastic Pipe Institute, 2003). The values calculated by the relationship are shown in parentheses below the measured values. The differences are due to the presence of color and ash, which affects the density measurement. Therefore, it is believed that for recycled PE, the yield stress is a more reliable indicator of the base resin density.

Table 3. Property summaries of five types of recycled polyethylene

Property	PCR-NAT (4) *	PCR-MC (15)	PIR-LD (1)	PIR-MD (1)	PIR-HD (1)
Density (g/cm^3)	0.957 ± 0.002 (0.2 %) † (0.959) ‡	0.955 ± 0.005 (0.5 %) (0.950)	0.952 (0.925)	0.942 (0.937)	0.970 (0.943)
MI (g/10 min)	0.70 ± 0.09 (12.9 %)	0.38 ± 0.10 (26 %)	0.80	0.66	0.32
% Ash	0.10 ± 0.04 (40 %)	1.11 ± 0.29 (26 %)	0.15	0.05	3.69
% PP	NA	3.7 ± 1.5 (41 %)	NA	NA	NA
Yield Stress (MPa)	30.53 ± 0.54 (1.8 %)	25.70 ± 1.45 (5.6 %)	11.63	18.14	21.67
Break Strain (%)	199 ± 100 (50 %)	90.4 ± 77.9 (86 %)	727	662	628
15% NCTL (hrs)	3.3 ± 1.4 (42 %)	7.8 ± 2.9 (37 %)	>300	>300	104
OIT (min)	16.5 ± 6.5 (39 %)	13.6 ± 7.0 (51 %)	6.3	61.4	18.2

* Number of samples

† Coefficient of variation
‡ Calculated from: Yield Stress = 560.3 (Density) – 506.9

The values for % PP found in this study may be a bit misleading. Although the highest value seen in the study was 6.3%, values as high as 19% have been seen by the author on samples outside of the study. Along with the yield stress, the break strain and the 15% NCTL stress crack values are the most important index properties for recycled PE and blends made with recycled PE.

The break strain is sensitive to defects and the 15% NCTL is an indicator of stress crack resistance with a notch. For the PCR resins, the break strain values varied from 9 to 302 % and the 15% NCTL values ranged from 1.8 to 14.8 hrs. The minimum required for AASHTO approved pipe resins is 24 hrs at a stress of 4.14 MPa. This is equivalent to 15%, if the yield stress is 27.59 MPa. A stress of 15% of yield was used in this study because the yield values for the resins involved varied greatly. One can easily see that PCR-HDPE is poor, in terms of stress crack resistance.

Contamination

The results of this study showed that simple particulates could be filtered out during processing and filtration with a 150 mesh screen, or equivalent, resulted in break strains easily in excess of 100 %. However, the results also showed that EVOH was resistant to removal by melt filtration. Apparently, EVOH is so soft that it can pass through the filter screens. This became clear during the BAM stress crack testing where recycled materials and blends with recycled resin had cracks initiate at EVOH particles.

Since the presence of EVOH could be a significant problem, a commercial compatibilizer was briefly evaluated to see if it could counter the deleterious effects of EVOH. Compounds made to assist blending between PE and EVOH are offered in the USA from Comtex, Inc, Dow Chemicals, and DuPont Chemicals. Addition of 1% compatibilizer produced a 40% increase in break strain from 125 to 175%. These types of additives should be looked at more closely, especially since some in the recycled bottle industry think the volume of EVOH in increasing in the recycled PE.

The effects of PP were determined by blending 2, 5, and 10% PP into a virgin pipe resin. The results showed that the density went down, the MI went up, and the 15% NCTL was unaffected up to about 5% PP. The most dramatic change came in the break strain where only 5% PP caused a 19% reduction. The effects could be worse in actual pipe because the samples made on a twin screw are blended better than manufactured pipe.

Blends

The preparation of the blends involved dry blending, gravity feeding, and melt extrusion through 150 mesh screens. Three passes through the twin screw extruder was standard. Then, plaques were made and properties measured. The properties measured included density, melt index, high load melt flow, % colour + ash, % ash, yield stress, break strain, 15% NCTL and oxidative induction time. Not every test was performed on every blend, but there were 59 of the 67 fully characterized and over 550 tests performed. Obviously, there is not enough space available to present many results, but the relationships between the properties and the percentage recycled can be discussed.

There were several generalities that could be made about certain properties.

- In all cases, the density, % colour + ash, % ash, yield stress, break strain, and OIT were linear with changes in composition.
- In all cases, the melt index, high load melt flow, and 15% NCTL were exponential with changes in composition.
- The % colour + ash and the % ash were very close to calculated values, which indicated that the blends were made well.
- The % break strain and 15% NCTL values had more scatter and were further away from their calculated values because of the presence of contaminants like EVOH. The PIR-HD, which had little or no EVOH, displayed properties very close to the theoretical line or curve.

Blends with Post-Consumer Natural Recycled (PCR-NAT) HDPE Resins

The PCR-NAT resins used for making blends contained less than 0.1% ash, yield strengths around 31.2 MPa, break strains around 300% and 15% NCTL times of about 2 hrs. Surprisingly, the scatter in the break strains averaged 38% on the threes samples used for blending. It is believed that this is due to the presence of EVOH in the recycled. EVOH particles were observed in failed BAM stress crack specimens, and its presence would not be detected by the ash analysis because it organic. A method is needed to quantify the % EVOH. Two examples of the changes seen with composition are shown in Figure 1.

The results of the blending and testing with natural PCR HDPE have produced the following findings.

- Only about 10% of natural PCR-HDPE can be added to virgin pipe resins and meet a 15% NCTL time of 24 hrs. However, the yield will be over 27.59 MPa, so the NCLS test will be less severe for this blend. That means that the limit might be closer to 15%.
- Dramatic improvements in stress crack resistance can be obtained by blending the NAT with either LLDPE or MDPE. A failure time of 50 hrs in the 15% NCTL test can be obtained with around 45% of added LL or 55% of added MD.

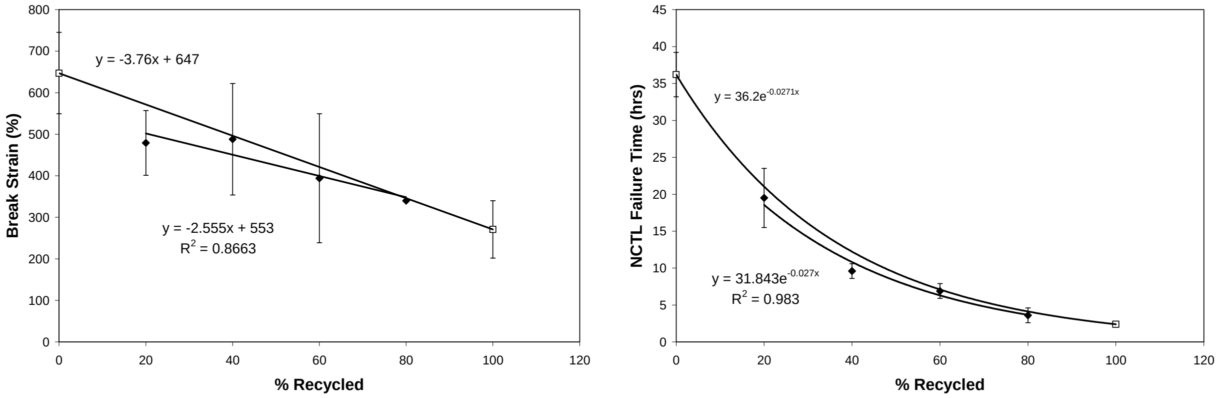

Figure 1. Plots of break strain and 15% NCTL versus % recycled for blends of VR1 with PCR-NAT

- Blends between NAT and MDPE are preferred because the yield stress remains higher for the MD blends. For example, the yield stress for 45% LL is around 20 MPa, while the yield stress for 55% MD is around 23.45 MPa. The AASHTO minimum density requirement for pipe resins is 0.948 g/cm^3, which correlates to a yield stress of around 24.14 MPa.
- The addition of only 10% LLDPE does very little to improve the properties of resulting blends.
- A blend of 50% VR3, 25% NAT and 25% MDPE has properties very close to a PPI certified pipe resin.

Blends with Post Consumer Mixed Colour Recycled (PCR-MC) HDPE Resins

The mixed colour PCR was the most contaminated and showed the most variability in its properties. Even though the properties of the blends changed predictably, some of the inherent scatter found in certain properties makes such predictions unreliable. However, it is believed that the relationships can be used as a guide for preparing blends with the understanding that actual blend testing will still be required. Generally, the break strain was below the predicted value because contaminants do not act in a linear and predictable manner. The 15% NCTL results were most often, but not always below the predicted exponential curve. Two examples of the changes seen with composition are shown in Figure 2.

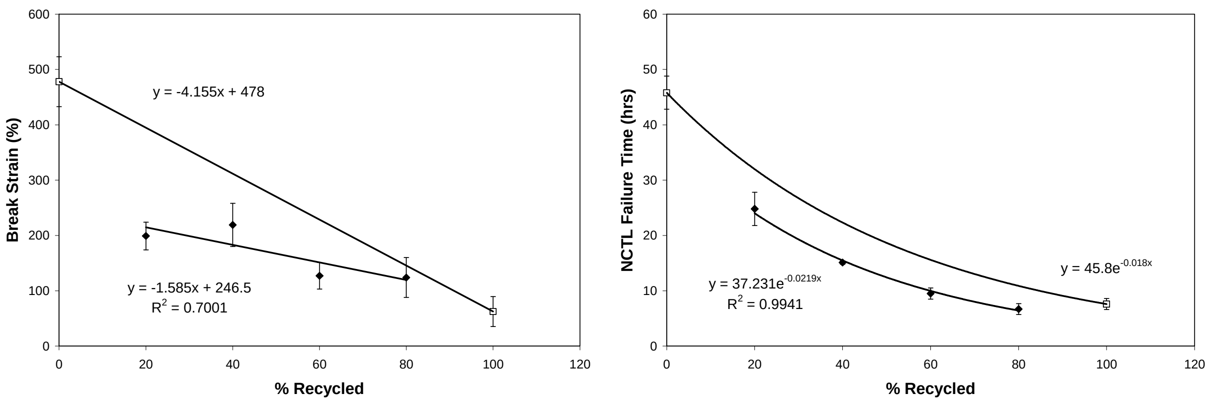

Figure 2. Plots of break strain and 15% NCTL versus % recycled for blends of VR1 with PCR-MC

The break strain curve is fairly typical for PCR-MC resin blends. Notice that there is both high scatter in the results, and the results are not close to the theoretical line. It is believed that the contaminants, particularly the EVOH would display behaviour such as this because individual particles cause early tensile breaks. This is unfortunate because it appears as if the theoretical relationships do not hold for PIR-MC resins. These resins may be the ones most often used because they give the largest cost benefit. PCR-NAT can actually sell for $0.10-$0.15/lb more.

And, perhaps the same reasoning applies to the 15% NCTL results. For this material, they were usually below the theoretical curve.

The results of the blending and testing with mixed colour PCR HDPE have produced the following findings.

- The maximum amount of mixed colour PCR that can be blended with one of the pipe resins and meet 24 hours of stress crack resistance is about 20%. And, since the 15% NCTL is less aggressive than the NCLS test in this case, a conservative number is closer to 15%.
- At 15% added MCR, all the AASHTO requirements of pipe resin would be met.
- The two different batches of mixed colour PCR (MCR1, MCRG) behaved dramatically different. The latter produced much better correlation to theory and had a much higher break strain, showing that there were fewer contaminants in the sample.

- The difference between the predicted and actual values of % strain-at-break might be used to evaluate the level of contamination in the recycled material.
- Much greater stress crack resistance may be required to offset the deleterious effects of contamination.
- The stress crack resistance can be dramatically improved by the addition MDPE to the mixed colour PCR. A 50:50 blend would produce a resin with about 200 hours in the 15% NCTL test. The yield stress would be reduced to about 3250 psi, so this must be kept in balance.
- The PIR-MD evaluated also improved the resistance to cracking, but not as much as the virgin MD.

Blends with Post Industrial Recycled High Density (PIR-HD) Polyethylene Resins

The PIR-HD was the recycled material that had the most consistent properties. According to the manufacturer, this material was a blend of PIR and PCR resins. It had a fairly high ash and colour content (3.9%) but showed very good strain at break of 684 % (COV = 6%) and 15% NCTL stress crack resistance of 98 hrs (COV = 10%). Unfortunately, continuous supplies of PIR resins are difficult to come by because they are most often sold on a lot-to-lot basis. For this reason, this project will focus on PCR resins because they are plentiful with a dozen or more suppliers. That said, the blends made with PIR-HD showed relatively low scatter and the lines or curves were close to the predicted values. Two examples are shown in Figure 3.

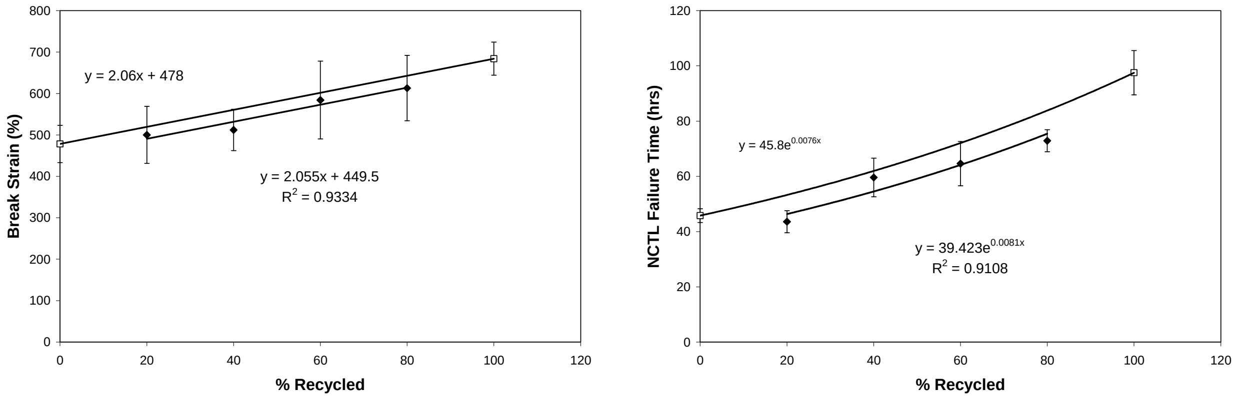

Figure 3. Plots of break strain and 15% NCTL versus % recycled for blends of VR1 with PIR-HD

The results of blending and testing with PIR-HD have led to the following findings.

- This PIR resin is apparently void of the contaminants found in PCR bottles that created high scatter in some properties, particularly break strain.
- A resin with a base density of around 0.943 g/cm^3 is an excellent resin for blending because it has a yield stress of around 21.72 MPa and stress crack resistance around 100 hrs.
- These test results served to validate the relationships found in the other blends.
- Blends of virgin resins containing up to 40% PIR-HD had yield stresses around 24.14 MPa, break strains above 550% and 15% NCTL times greater than 40 hrs. This blend would meet the resin property requirements found in AASHTO M294 for pipe.

The BAM Stress Crack Test

The BAM test is a stress crack test without a notch that has shown to be sensitive to both the fundamental stress crack resistance of a sample and the amount of residual stress or flaws present in a sample. It was used in the 1990's on both textured geomembranes and double track fusion seams to improve both processes (Thomas and Woods-DeShepper 1993, Thomas, *et al*. 1995). Its use here was to determine if the flaws in recycled resin blends could be overcome during blending. The test was performed on several blends and the results are shown in Table 4. The break strain values are also shown because there may be a relationship between BAM stress crack resistance and % break strain.

Notice that several of the blends exceeded 200 hours in the test. This is encouraging since some specimens of the 3 virgin resins failed in less than 300 hours. It is also encouraging for resins containing PCR-MC because 1 blend had all five specimens last longer than 300 hrs. This test may become very important for the use of recycled resins. One important feature of the BAM test is that the fractured surface of broken specimens can be examined microscopically to determine where the crack started. In the specimens tested during this project, excluding virgin resins, the cracks were initiated by a contaminant. This included a variety of different coloured hard particles, and soft particles, believed to be EVOH. Most of the failures in PCR containing samples occurred at a soft, rubbery particle.

Table 4. Results of the BAM stress crack test

Sample	BAM Failure Time (hrs)	% Strain-at-Break
VR1	>268 ± 38*	465 ± 88
VR2	>300 ± 97	625 ± 118
VR3	>267 ± 47	575 ± 144
VR3 + 20% MCR1	87 ± 33	461 ± 65
VR2 + 20% NAT	93 ± 32	534 ± 120
50% VR3 + 25% MD + 25% MCRG1	>300	601 ± 107
50% VR3 + 25% MD + 25% NAT	>206 ± 89	631 ± 188
VR3 + 40% PIR-HD	>242 ± 100	643 ± 97

*Some specimens exceeded 300 hrs

CONCLUSIONS

The results of this study have identified several types of recycled resins, produced test results to show what an industry wide average sample might be, and demonstrated how contaminants can affect certain properties. Additionally, many blends were prepared and characterized, which showed the relationships between key properties and blend composition. This work confirmed earlier work on blends of virgin resins and PCR natural (Miller, et al. 2000, Stefanovski, et al. 2002) And finally, the results proved that blends could be prepared with up to 40% recycled HDPE that meet the AASHTO M294 property requirements for resins used to make corrugated pipe.

The results also strongly suggest that much better blends can be made than the ones reported on here. The MDPE used to improve the PCR-MC properties has a density of 0.936 g/cm^3. There are other resins with densities up to 0.945 g/cm^3 that also have very good stress crack resistance. The use of these resins will allow more recycled resin in a blend without dropping below the required yield stress of about 24.14 MPa. Therefore, the resin property requirements cited in AASHTO M294 can be maintained while the focus of additional research can be on long-term tests, like the BAM test on plaques and a creep rupture test on pipe.

The next phase of this study is to make 10 samples of pipe from virgin HDPE, virgin MDPE, PCR-NAT, and PCR-MC, in two separate manufacturing plants. The ten formulations have been selected and have from 15 to 60 % recycled content, predicted % break strains of 400 to 550 %, 15% NCTL times from 29 to >65 hours, and cost saving from $0.01 to $0.06 per pound. The pipe samples will be evaluated in terms of long-term creep and creep rupture to demonstrate if blends containing recycled resins can approach the service lifetimes of virgin resins.

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REFERENCES

Miller, P., Kosior,E., Masood, S., and Iovenitti, P., 2000, Linearity and non-linearity of mechanical properties in blends of virgin and recycled HDPE's, , SPE Antec Proceedings, Vol. III, Orlando, 2893-2897.

Plastic Pipe Institute 2003, Design service life of corrugated HDPE pipe, Technical Report, TR-43.

Scheirs, J. 1998, Polymer recycling: science, technology and applications, John Wiley & Sons, New York.

Stefanovski, V., Masood, S., Kosior, E., Iovenitti, P, and Sbarski, I. 2002, Pipes from recycled high density polyethylene blends", SPE Antec Proceedings, Vol. III, San Francisco, 3817-3821.

Thomas, R. and Woods-DeSchepper, B. 1993, Stress crack testing of unnotched HDPE geomembranes and seams, Proceedings of the 7th GRI Seminar, Philadelphia,PA, 116-125.

Thomas, R., Kolbasuk, G. and Mlynarek, J. 1995, "Assessing the quality of HDPE double track fusion seams", Proceedings of the Sardinia '95 Landfill Conference, Sardinia, Italy.

Thomas, R. 2006, Performance and quality control of corrugated pipe manufactured with recycled polyethylene content, Preliminary Interim Report, NCHRP Project 04-32.

Thomas, R. 2008, Performance and quality control of corrugated pipe manufactured with recycled polyethylene content, Preliminary Interim Report II, NCHRP Project 04-32.

Wu, S., Sehanobish, K., and Jivraj, N. 2000, Defect analysis and high density polyethylene durability, SPE Antec Proceedings, Vol. III, Orlando, 3143-3147.