

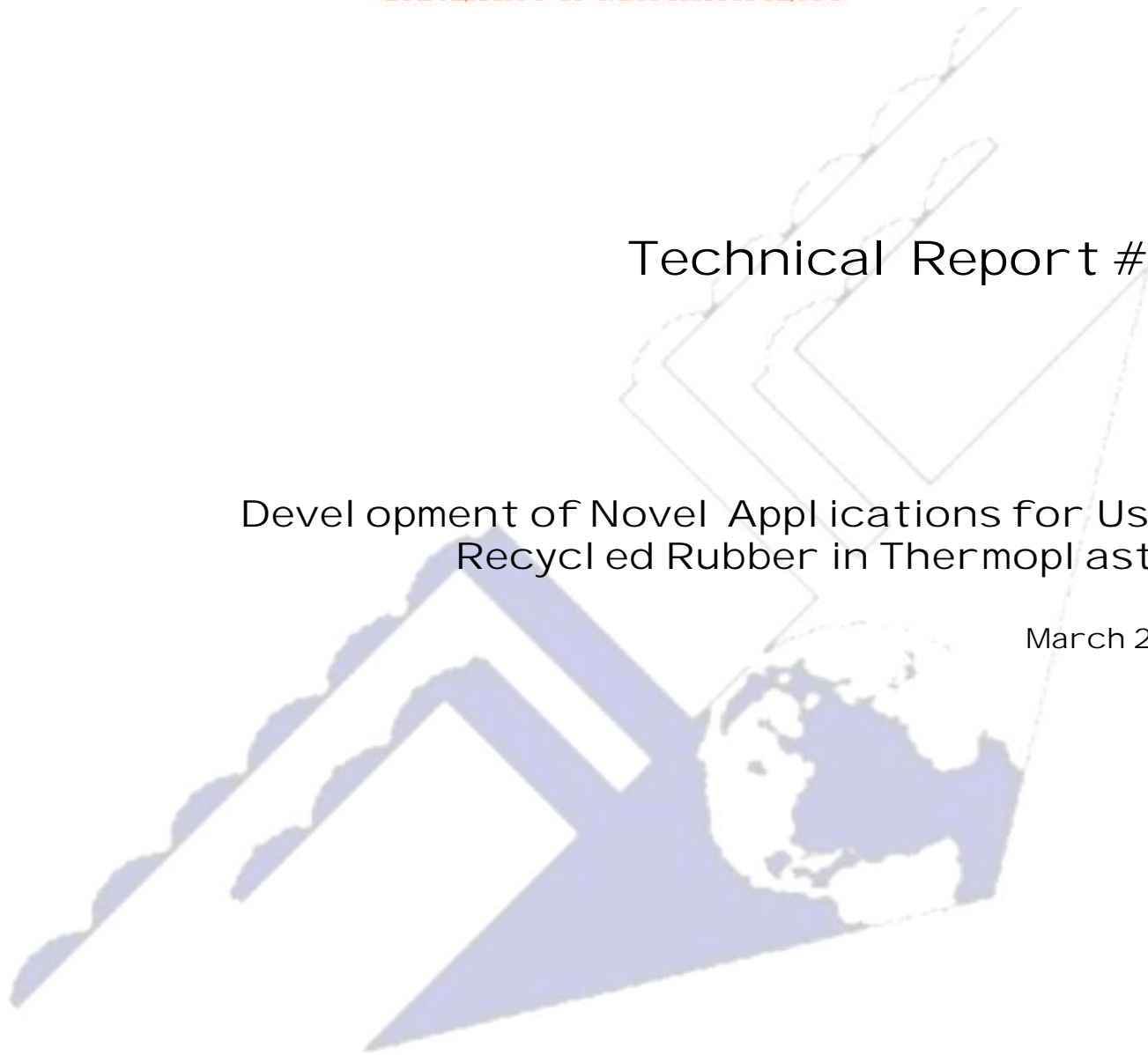
CHELSEA CENTER FOR RECYCLING AND ECONOMIC DEVELOPMENT

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Development of Novel Applications for Using
Recycled Rubber in Thermoplastics

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Development of Novel Applications for Using Recycled Rubber in Thermoplastics

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List of Acronyms

DMA	Dynamic mechanical analysis
EPDM	Ethylene propylene diene rubber
H₂O₂	Hydrogen peroxide
H₂SO₄	Sulfuric acid
HDPE	High-density polyethylene
KMnO₄	Potassium permanganate
MFI	Melt flow index
MnO₂	Manganese oxide
PP	Polypropylene
SBR	Styrene-butadiene rubber

1. Abstract

Rubber production and use in the United States is rising, but methods to dispose of scrap rubber are limited at best. New uses and markets need to be developed for recycled scrap rubber. One potential method is to reuse the scrap rubber by blending it with thermoplastics, for example, polypropylene (PP). By varying the blend, materials ranging from an impact-modified thermoplastic to a thermoplastic elastomer can be obtained. This study focused on making thermoplastic elastomers, which use larger quantities of scrap rubber. The thermoplastic elastomer would be recyclable itself so that scrap produced from its use could also be recycled.

Rubber particle size, the melt flow index (MFI) of the PP, the percentage of rubber by weight, and the type of thermoplastic were investigated for their effects on the physical properties of the rubber/plastic blends. Techniques to improve the quality and compatibility of the scrap rubber/plastic blends were developed. These investigations showed the MFI of the PP was a key factor in the mechanical properties of the blends. By proper selection of the components and compatibilization techniques, the blends can be tailored for specific applications. The results of this work can guide manufacturers in the proper selection of materials and techniques to use recycled rubber in blends for a variety of product applications.

Possible applications for these blends, including sports surfaces, were investigated. The physical properties and costs of some of the blends were compared to commercial products and were shown to be competitive.

2. Background

Rubber production and use in the United States is on the rise with the majority of the rubber going into the production of tires. This increase in rubber use has outgrown the United States' ability to properly dispose of scrap tire rubber. The problem is compounded by the nature of the tire rubber itself, which is a thermoset material (it does not easily melt back into soft rubber). The U.S. Environmental Protection Agency estimates that approximately 242 million tires are discarded every year. That's one tire for every person in the United States.¹

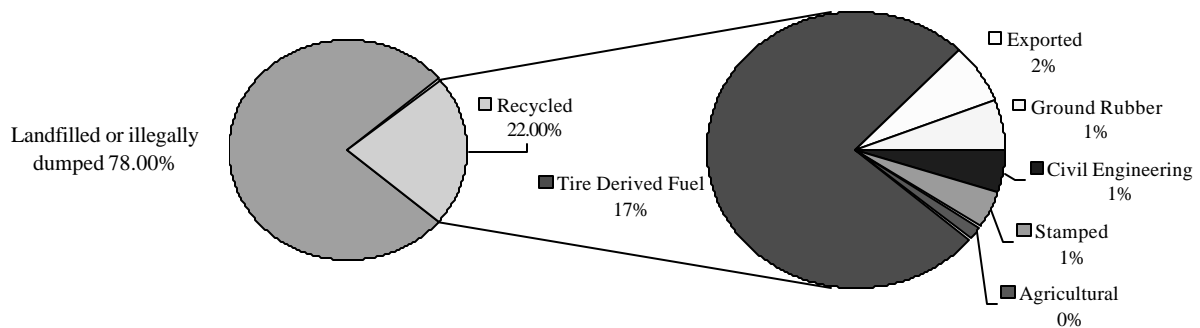


Figure 1. Pie graph of markets and uses of recycled tire scrap²

As shown in Figure 1, the majority of scrap tires in the United States are buried or stockpiled. Tire stockpiles are unsightly and provide homes and breeding grounds for disease-spreading vectors such as rats and mosquitoes. Tire stockpiles also present the danger of self-sustaining fires that cause air and water pollution and are quite expensive to extinguish and clean up. For example, a pile of one million tires in Everett, Washington, caught fire in the early 1980s. After the fire was extinguished, the clean-up costs were estimated to be \$3.30 per tire. Before the fire, the clean-up estimate was \$0.25 per tire.³

Only 22% of tires are recycled. Of those, 17% are used for tire derived fuel, 2% are exported, 1% is ground or stamped, and 1% is used in civil engineering applications. An example of a civil engineering application is the addition of crumb rubber to asphalt. The new asphalt produces a quieter and tire friendly road.⁴ Crumb rubber has also been used in asphalt at bridge approaches. At the Androscoggin River Bridge in Brunswick, Maine, crumb rubber from 500,000 old automobile tires was used to create a lightweight bridge approach embankment.⁵

While scrap tire disposal is a nationwide problem, most recycling and disposal programs are controlled at the state level. Three states have no scrap tire regulation, while 33 states have some system for scrap tire recycling. A general system for scrap tire recycling can be found in Table 1. Some states assess taxes on new tires to help pay for regulation of scrap tires and market development programs. The Environmental Protection Agency estimates that six million scrap tires are generated in Massachusetts each year⁶.

Table 1. Scrap Tire Recycling System⁷

1. Purchase of new tires and state imposed tax for scrap tire recycling
2. Tires become worn and should be recycled
3. Scrap tires are collected at state regulated collection facilities
4. Scrap tires are collected and transported to a processing facility, which is also monitored by the state
5. Processing facility reduces the size of the scrap tires and or processes them for additional recycling
6. Additional recycling consists of obtaining oils, carbon black, and steel wire

The structure of the rubber polymer itself makes recycling difficult. Tire rubber is a thermoset, meaning the polymer is crosslinked into a network. These crosslinks are usually covalent bonds between polymer chains, which are difficult to break by simple means. Once the polymer chains have been crosslinked, it is no longer possible to reform the material simply by heating the polymer, as is done with thermoplastics like polyethylene terephthalate (PET). Crosslinking can be introduced into the polymer by heat and/or chemical means. In rubber, crosslinking is more commonly known as vulcanization, which uses heat and sulfur.

Other recycling methods such as grinding must be used to recycle a thermoset. The ground rubber, called crumb, can be used alone or mixed with thermoplastics to achieve desired properties.⁸ Tires also contain other components, such as steel wire, carbon black, and petrochemicals, which can make recycling complex. Figure 2 outlines a tire's composition.

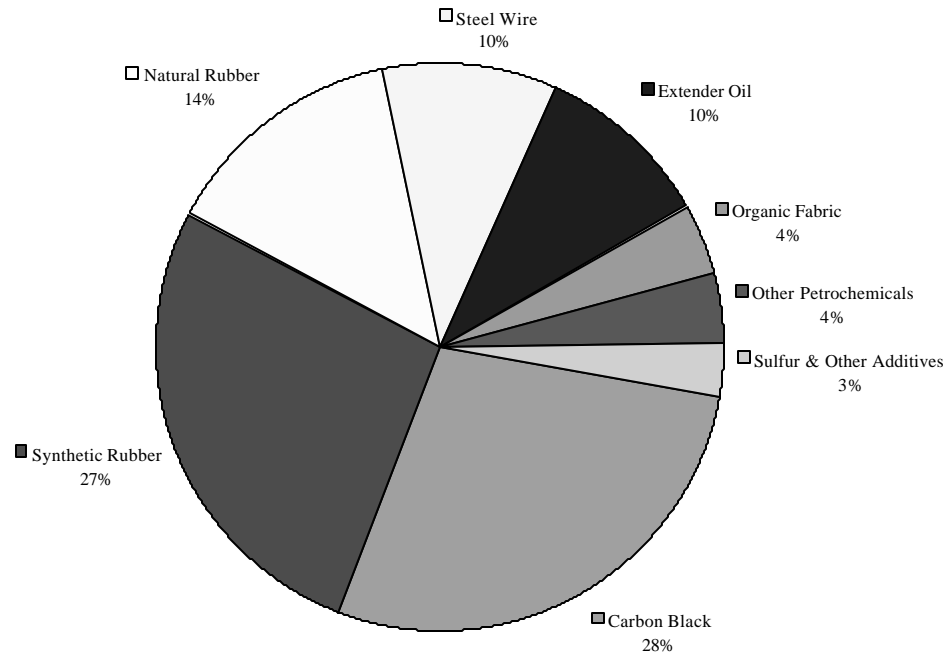


Figure 2. Components of tires⁹

There are two main methods for grinding scrap tires. The first method is the ambient grinding system and the second is the cryogenic grinding system. Depictions of the ambient grinding system and cryogenic grinding system can be seen in Figures 3 and 4. Magnets are used throughout the grinding process to retrieve the small particles of metal that may be found in tires.

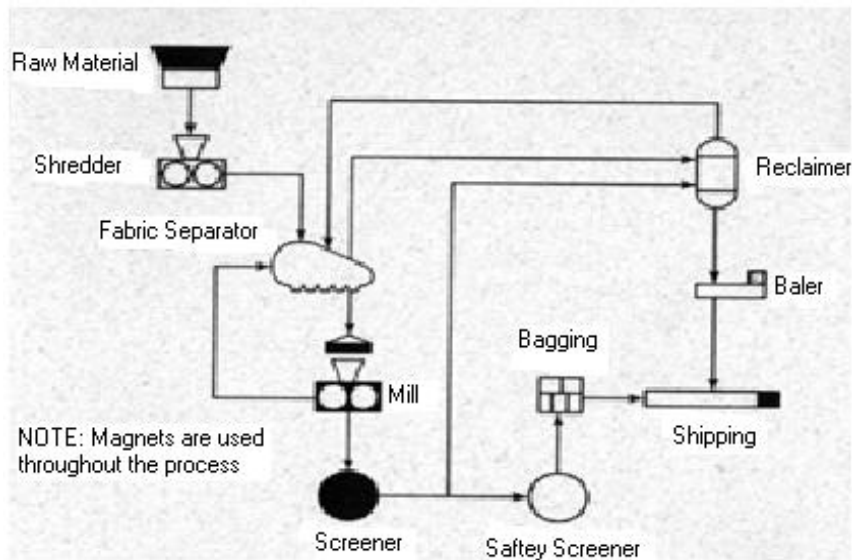


Figure 3. Ambient grinding process¹⁰

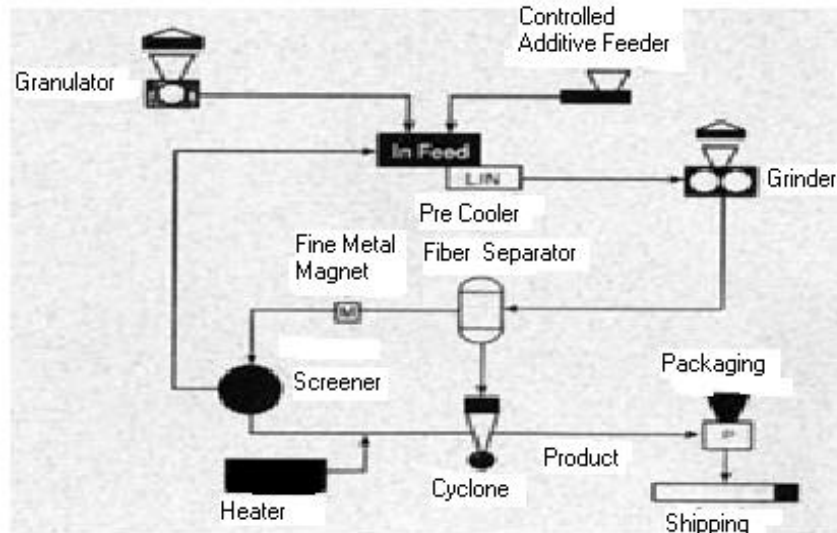


Figure 4. Cryogenic grinding process

Scrap rubber can be blended with thermoplastics such as PP to produce thermoplastic elastomers with a range of properties. These materials can be used in conventional thermoplastics processing equipment. The unique characteristics of thermoplastic elastomers make them an attractive alternative to conventional elastomers in a variety of markets such as the automotive industry. The potential to convert a conventional elastomer (thermoset) into a thermoplastic elastomer through blending offers the potential for new market applications for scrap rubber.

Prior work in blends has included adding tire rubber to polystyrene to increase the impact strength and toughness of the polystyrene.¹¹ An impact-modified polystyrene may contain 20% rubber in the blend. Other research has studied blends of high-density polyethylene (HDPE) with recycled tire rubber.¹² In this case the authors found decreased tensile strength with increased rubber content, decreased hardness with increased rubber content, and increased ductility above 5% rubber content. Chidambaram and Kim studied the effect of surface treatment of rubber particles on reactive blends with polymethyl methacrylate and found that surface treatments could be used to enhance the mechanical properties of the blends.¹³

It may be possible to develop a thermoplastic elastomer by blending ground scrap tire or rubber with either a virgin or recycled PP. These blends may have properties similar to those of dynamically vulcanized blends. Dynamically vulcanized blends are commercial products prepared by crosslinking raw rubber, such as ethylene propylene diene rubber (EPDM) or other rubber, during melt mixing with molten plastic, generally PP.¹⁴ The resulting dynamically vulcanized blend has small particles of crosslinked rubber imbedded in a matrix of PP. The focus of this research was to develop blends of ground scrap rubber with PP to develop materials with a useful range of properties for new markets. In addition to laboratory development of plastic/rubber blends, an analysis of the market was performed to determine potential applications for the new material. The cost-effectiveness of the blends in potential market applications was also assessed.

3. Scope of Work

3.1 Market Analysis

A market analysis was performed to determine potential applications for the rubber/plastic blends. Initially, markets with less stringent requirements were targeted, including roofing materials and sports surfaces. A cost analysis was performed on potential applications to compare recycled rubber/plastic blends to commercially available materials.

3.2 Blend Development

3.2.1. Literature Survey

A brief review of the literature was performed to assess the current state of the art.

3.2.2. Obtaining Materials

PP with various MFI was obtained for the blending experiments. Virgin PP was used to better control the experimentation. Elastomer scrap was obtained from the industry partner (Erickson Materials^{*}) in two mesh sizes and two elastomer types, EPDM and SBR. Experiments were performed on both materials. A small sample of cryogenically ground rubber was also evaluated early in the project. A variety of grafting agents and compatibilizers were obtained from various sources.

3.2.3. Blending Studies

This phase comprised the bulk of the work in the project. A large number of variables were evaluated in the blending study:

- Type of ground rubber – cryogenic vs. Erickson Micropowder®
- Rubber material – EPDM and SBR
- Ratio of rubber to plastic in blend
- Mesh size of the rubber – 170 and 80 mesh
- Melt Flow Index of PP
- Compatibilization techniques
 - Surface treatment of rubber followed by addition of maleated PP
 - Reactive blending

In addition to the material variations, experiments on the processing conditions and variables were performed.

^{*} Erickson Materials closed their operations in late 1999. Similar material is available in Massachusetts from Rouse Polymeric, which purchased Erickson's equipment.

3.2.4. Physical Property Evaluation

A variety of physical tests were performed on the blends. These properties included hardness, tensile strength, ultimate elongation, and dynamic mechanical properties. These properties were used to optimize the blending conditions and to assess the blends compared to commercially available materials for the target application.

4. Experiments and Description of Approach

4.1. Market Analysis

Some potential applications for scrap rubber/plastic mixtures are flooring in ice rinks and weight rooms, playgrounds, running tracks, and commercial and residential roofing.

After the markets and products have been identified, a scale-up cost must be estimated. The quickest and most commonly used estimation method is the power law or exponential law. The power law formula for cost estimation can be seen below in equation (1)¹⁵

$$(C_a/C_b) = (S_a/S_b)^x \quad (1)$$

where C_a is the cost of a, S_a is the size of a, x is the exponent, C_b is the cost of b, and S_b is the size of b. The exponent, x , is dependent upon the type of operation or project, but usually is in the 0.6-0.8 range. Some typical values for x are 0.86 for a cement plant, 0.81 for a glass lined reactor with a drive motor, and 0.73 for an acetylene plant.¹⁶ This formula can be used to perform a quick estimate of the cost-effectiveness of a project. This is an important step in the decision to compete in the marketplace at full capacity. See Tables 17 and 18 for a sample application of the Power Law Equation.

4.2. Blend Development

A variety of techniques and materials were evaluated to develop rubber/thermoplastic blends. Variables included the type and size (mesh) of rubber, the type of PP (MFI), and the compatibilization technique (surface treatment or reactive blending). The methodology is described below.

4.2.1. Materials

The materials used in the blending are listed in Table 2.

Table 2. Materials Used

Plastic Materials			
	Commercial Name	Manufacturer	MFI (g/ 10 min)
PP	Tenite	Eastman Co.	12
		Fina Co.	4.5
	Profax	Montell Co.	0.45
Ethylene-Octene Copolymer	Engage 8100	Dow Chemical Co.	1
Rubber Materials			
	Formula	Manufacturer	Mesh size
Recycled SBR		Erickson Inc.	80
Recycled EPDM		Erickson Inc.	80, 170
Additives			
	Formula	Manufacturer	Concentration (%)
t-Butyl Hydroperoxide		Aldrich Co.	35
Potassium Permanganate	KMnO ₄	Aldrich Co.	90
Hydrogen Peroxide	H ₂ O ₂	Aldrich Co.	30
Sulfuric Acid	H ₂ SO ₄	Aldrich Co.	99.5
Maleated PP		Aristech Chemical Co.	

4.2.2. Treatment and Blending Procedures

4.2.2.1. Pure Blending

Materials were mixed in a Rheocord System 40 (Haake Buchler). The mixer was preheated until the chamber temperature was stable, which took about 30 minutes. The required screw speed was set and the plastic material was added first. The rubber portion was added when the plastic material was completely melted, indicated by a stabilized torque reading, usually after 4 to 5 minutes. The mixing was stopped after the designated time (two to ten minutes), or when the torque became constant. Then, the mixer was cleaned and purged for the next trial. A variety of blends were prepared including blends using rubber ground by cryogenic and ambient processes, different types of rubber (ethylene propylene diene rubber (EPDM) and styrene butadiene rubber (SBR)), different ratios of PP to rubber, and different PP grades (MFI). Table 3 shows the composition of blends prepared by varying the ratio of rubber to PP.

Table 3. Composition of Experimental Blends

% EPDM	% PP	% SBR	% PP
10	90	40	60
20	80	50	50
30	70	60	40
40	60	70	30
50	50	80	20
60	40		
70	30		
80	20		

4.2.2.2. Surface Treatment Blending

To improve the compatibility between the rubber and PP, the surface of the rubber was treated to produce hydroxyl groups on its surface, which would be capable of reacting with maleated PP. The maleated PP would be expected to make the rubber compatible with the PP. To surface treat the particles, the rubber particles were dispersed in an aqueous acetone solution (10% acetone) and were oxidized by 2% KMnO_4 (potassium permanganate) by weight. After 24 hours, the purple color of the KMnO_4 was gone, indicating the completion of the reaction. The byproduct, MnO_2 (manganese oxide), was further oxidized for separation by 30% H_2O_2 (hydrogen peroxide) with 0.1% H_2SO_4 (sulfuric acid) aqueous solution. The rubber was washed with water until the filtrate was neutral. Finally, the treated rubber was air-dried.

Blends were prepared using the treated rubber and PP by following the pure blending procedure described above, except that maleated PP was added one minute after the rubber portion. Maleated PP was varied from 0 to 20% by weight. The mixing was stopped after the designated time or when the torque showed a constant value. Then the mixer was cleaned and purged for the next trial.

4.2.2.3. Reactive Blending

Reactive blends of untreated rubber and PP were prepared by following the pure blending procedure, except that 0.7% (of rubber weight) *t*-butyl hydroperoxide was added right after the addition of the rubber portion. The trial was stopped after the designated time or when the torque became constant. Then the mixer was cleaned and purged for the next trial.

4.2.3. Molding

The rubber/plastic composite was removed from the mixer and allowed to cool to room temperature. Then the sample was ground using a laboratory mill (Thomas Wiley, model 4) with a 40 mesh screen. If the particles were larger than 40 mesh, efficient compression molding was problematic due to large air gaps or voids caused by the larger particle sizes. This reduced the favorable properties of the samples. When this was the case, the grinding procedure was repeated. The procedure was repeated more often for the high rubber-content compounds.

Compression molding was performed in a heated press (Carver, Model C). The machine was preheated to 225 °C until stable. The square mold was made from a 1.5 mm sheet of aluminum. The square mold's interior dimensions were 90 mm × 125 mm and the exterior dimensions were 178 mm per side. Sandwiching five plates together formed the complete mold. The order and type of plates from top to bottom can be found in Table 4. This assembly was prepared using 76.2 mm × 101.6 mm sheets. For molding, 16 grams of material were placed into the sandwich mold, which was then placed into the compression molding press. It was preheated for five minutes, then compressed to 30 MPa for five minutes, slowly increasing the load to 100MPa for another five minutes. It was cooled to room temperature under a 100 MPa load using a Schrader cooling press. The sheet was then removed and die cut for the appropriate test.

Table 4. Complete Compression Molding Assembly

Order from top to bottom	Material
1	Aluminum top plate 1.5mm thickness
2	PTFE sheet
3	Frame
4	PTFE sheet
5	Aluminum bottom plate 1.5mm thickness

4.2.4. Testing

The tensile test bar was die cut with a ½ scale ASTM D412 die. A diagram and the dimensions of the half-scaled ASTM D412 die can be seen in Figure 5 and Table 5.

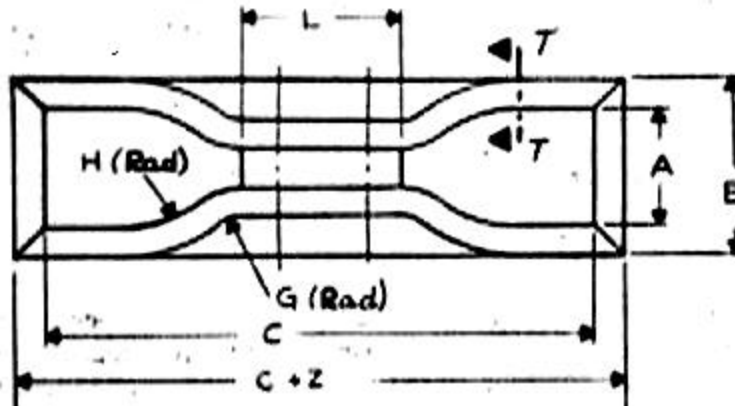


Figure 5. Diagram of half scale ASTM D412 die

Table 5. Dimensions of Half Scale ASTM D412 Die

Dimension	Units	Die "C"
A	mm	12.5
B	mm	20.0
C	mm	57.5
G	mm	7.0
H	mm	13.5
L	mm	16.5
Z	mm	6.5

The tensile testing was performed using an Instron 6025. A crosshead speed of 5.1 cm/min was used during testing. The elongation was determined by using crosshead displacement and the gage section as the original length, because an extensometer for high strains was not available.

A razor blade was used to cut the molded sheet into four strips for Shore A hardness testing. The strips, which were 0.9 cm thick, were stacked on top of each other to meet the thickness requirements of the ASTM D2240 test. After the strips were cut and stacked, the test was performed using a hand-held Shore A hardness tester with a total of 10 readings. The average of the ten readings was taken as the hardness of the experimental blend. After completing the testing, the data was compiled and evaluated.

5. Results

5.1. Blend Development

A variety of blends and blending techniques using recycled rubber in thermoplastics were evaluated. The results of the blending experiments are described below.

5.1.1. Type of Ground Rubber (cryogenic vs. Erickson Micropowder®)

As mentioned above, there are two ways to obtain ground rubber, cryogenic grinding and ambient grinding. Erickson Materials, Inc. used ambient grinding methods. In order to investigate the difference between cryogenically ground rubber and Erickson's Micropowder®, experiments were performed by preparing blends using 40% by weight of each of the above types of styrene-butadiene (SBR) (80 mesh) and 60% PP (12 MFI). Some blends were prepared by adding maleated PP to make the elements more compatible. The rubber's surface was not treated prior to blending in this set of experiments.

Figure 6 shows the ultimate tensile strength versus the concentration of maleated PP. Two conclusions can be drawn from the tensile strength curves. First, the ultimate tensile strengths of the blends using the two different types of ground rubber are similar. Second, the addition of the maleated PP has little effect on the ultimate tensile strength of the blends using untreated rubber.

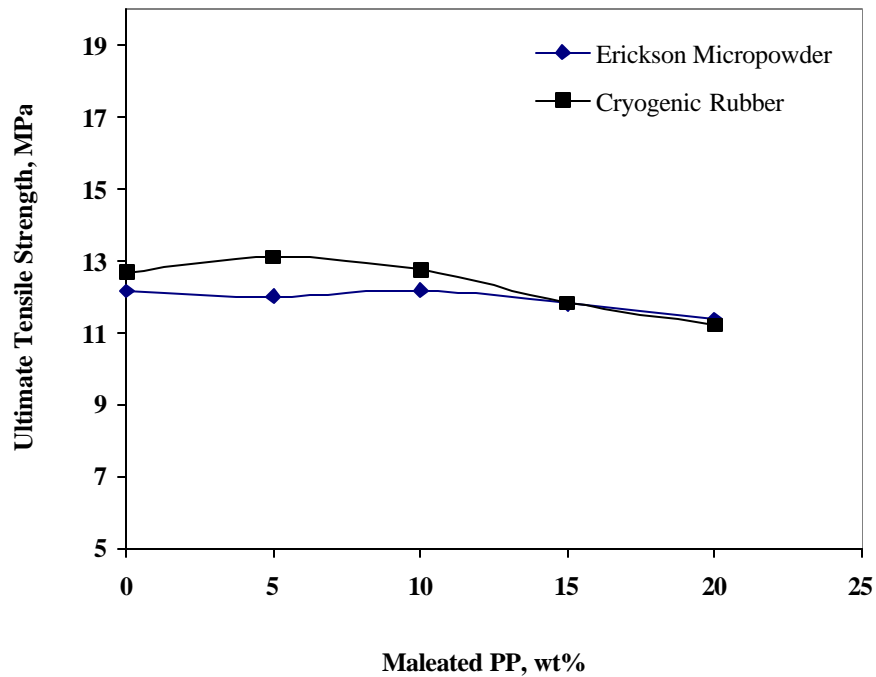


Figure 6. Ultimate tensile strength comparison of different ground rubber in thermoplastics

However, the ultimate elongation data reveals differences between the two types of ground rubber. Figure 7 shows the ultimate elongation versus the concentration of maleated PP. The blend using Erickson's Micropowder shows a higher elongational capability than that of the cryogenic rubber. However, the elongation did not exceed 20% for either of the blends. The addition of the maleated PP had a negligible effect on the elongational capability of the blended product. The particle shape obtained from these two processes explains the higher elongational capability of the Erickson Micropowder. As shown in Figure 8, the cryogenically ground rubber gives a flat fracture surface, while Erickson's Micropowder has a multilobed morphology. On a microscopic level, the flat surface has less surface area for the same particle size than a multilobed morphology. The increased surface area and possibly mechanical interlocking between the rubber and PP provides better adhesion and therefore more favorable ultimate elongation. Recall, however, that overall the blends tended to have poor elongational capability.

Visual inspection of the tensile test specimens showed that blends made from cryogenic rubber had many voids, while those made from Erickson Micropowder had fewer voids. The results can be explained by taking the size-reduction process into account. The cryogenic size-reduction process exposes new rubber particle surfaces to the air during the grinding process. The resulting surface oxidation will make the rubber particle surface more polar, giving it better adhesion to maleated PP. On the other hand, Erickson's wet milling technique grinds the rubber in water. Therefore, less surface area is exposed to oxygen during the size reduction process, resulting in less oxidation, a less polar rubber particle surface, and weaker adhesion with maleated PP. This effect is not consistent, however, with the trend seen in the data, and another explanation must be found.

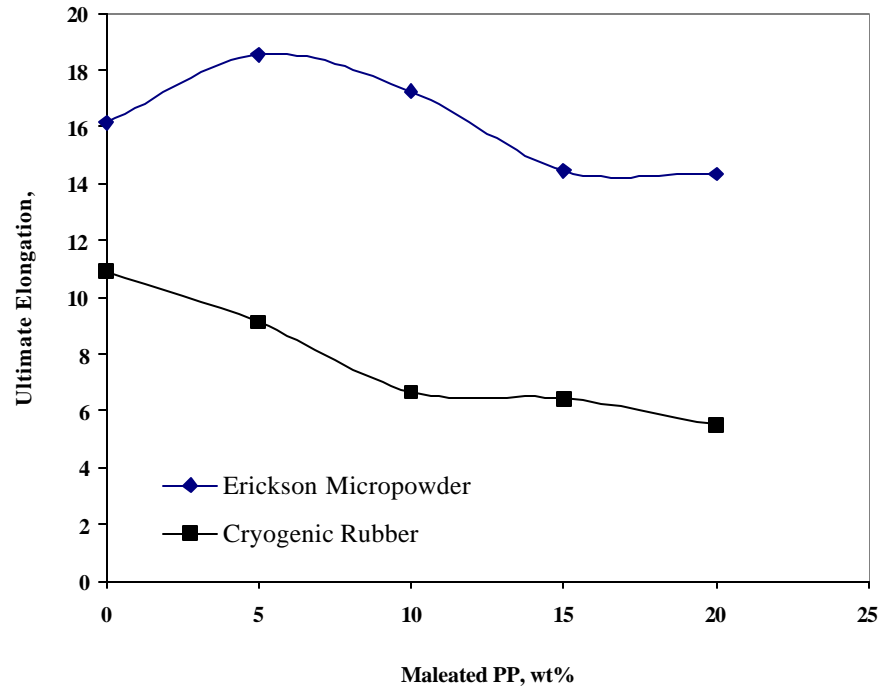


Figure 7. Ultimate tensile strength comparison of different ground rubber in thermoplastics

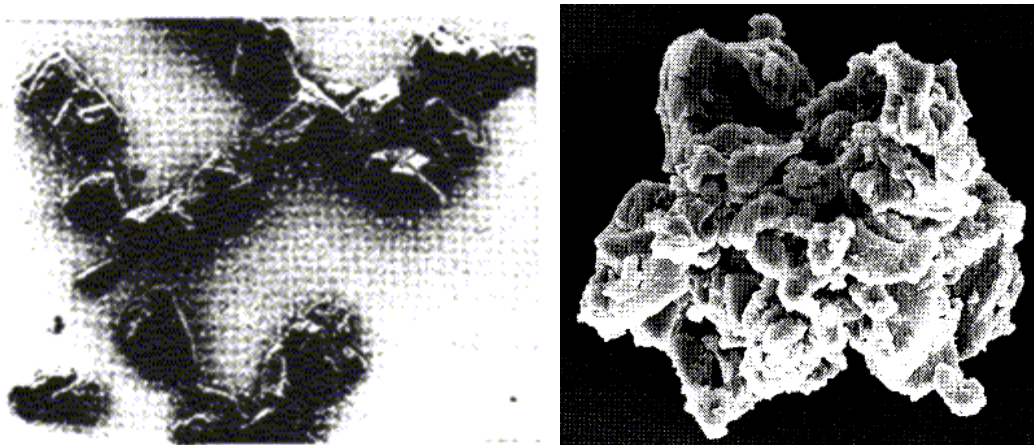


Figure 8. Cryogenic Rubber 100x magnification (left)¹⁷ and Erickson's Micropowder 325x magnification (right)¹⁸

5.1.2. Percentages and Types of Rubber

There were two different types of recycled rubber used in the blending and testing, SBR and EPDM. Table 6 below shows the results for the testing of the recycled EPDM/PP blends using 12 MFI PP.

Table 6. Testing Results for Recycled EPDM/PP Blends

% EPDM	Tensile Stress (MPa)	Standard Deviation (Stress)	Tensile Strain (%)	Standard Deviation (Strain)	Hardness Shore A
10	21.7	0.88	17.98	1.78	
20	17.7	0.68	20.55	3.56	
30	12.9	1.74	14.63	3.05	
40	10.1	0.89	13.47	2.87	
50	7.7	0.66	13.17	3.42	96
60	6.1	0.26	18.84	5.02	94
70	4.4	0.42	29.17	10.73	88
80	2.0	0.57	23.18	8.10	84

Graphical analysis of the results of the physical properties testing in Table 6 can be seen in Figures 9 through 11 below.

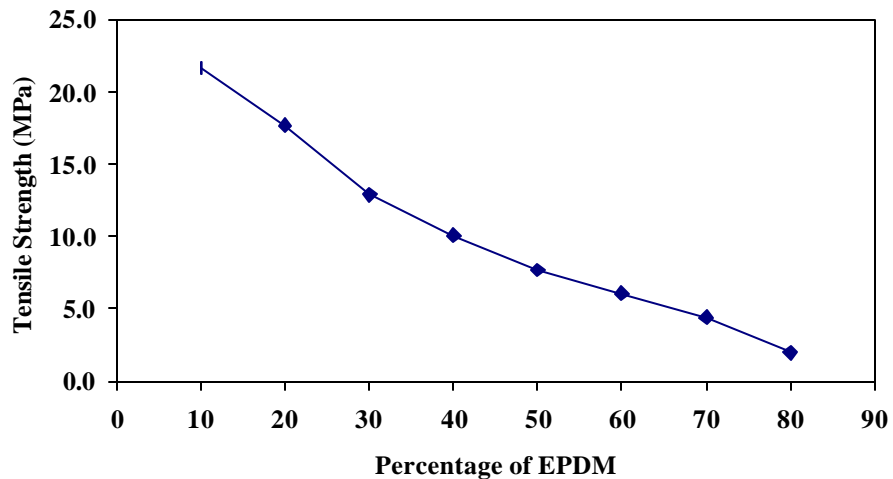


Figure 9. Tensile strength of recycled EPDM/PP blends

Figure 9 and Table 6 above show that as the percent of EPDM in the blends increases, the tensile strength of the blend decreases. The EPDM has a lower tensile strength than the PP and therefore as more of it is added to the blend, the tensile strength of the blend decreases.

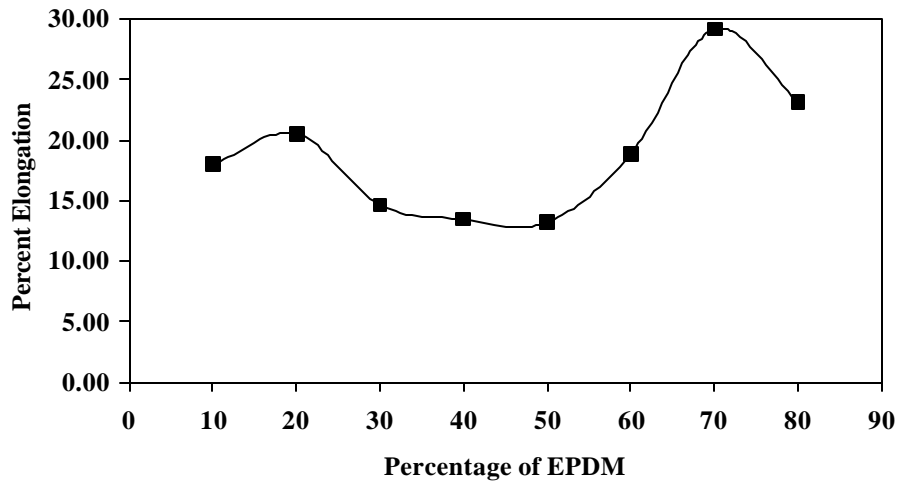


Figure 10. Percent elongation of recycled EPDM/PP blends

Figure 10 and Table 6 above show that as the percent of EPDM increases, the elongation is varied. The 20% EPDM and 80% PP blend has an elongation of about 21%. This is the high point for the lower percentage EPDM blends. Therefore the 20% EPDM and 80% PP blend appears to be the optimum for high elongation in the low percentage EPDM blends. The 70% EPDM and 30% PP blend has an elongation of 29%. This is the high point for the higher percentage EPDM blends. The 80% EPDM and 20% PP blend has an elongation of 23%, and the 60% EPDM and 40% PP blend has an elongation of 19%.

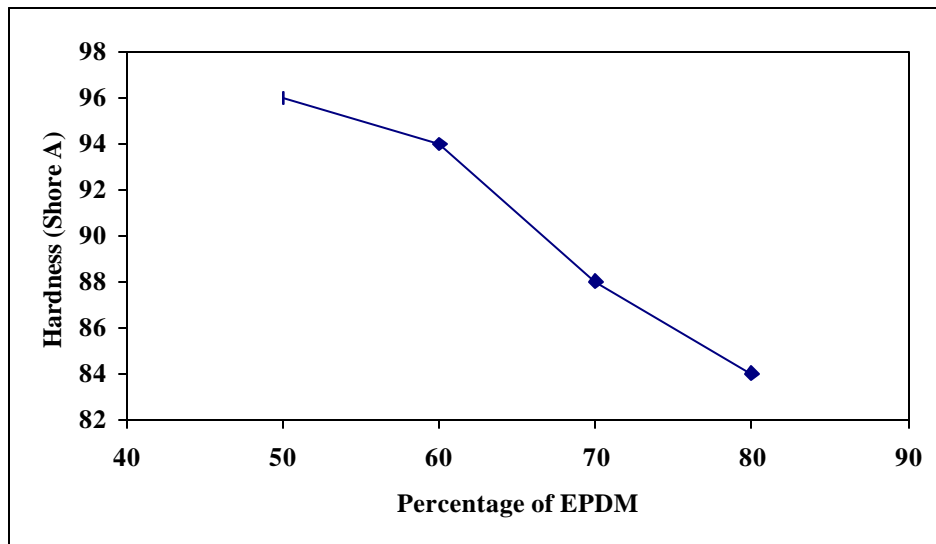


Figure 11. Hardness of recycled EPDM/PP blends

Figure 11 and Table 6 above show that as the percentage of EPDM in the blend is increased, the hardness, measured on a Shore A scale, decreased. The recycled EPDM is softer, meaning that the T_g of the rubber is lower than that of the PP. As the percentage of recycled EPDM increases, the hardness decreases.

Dynamic mechanical analysis (DMA) of some of the blends revealed the expected results: the existence of two phases in these materials – a rubber phase and a PP phase. Figure 12 shows G' , G'' and $\text{Tan } \delta$ for the 50% EPDM rubber blends. They show the T_g (measured by maximum in $\text{Tan } \delta$) for the EPDM, at -51°C , and for the PP at -1°C . As expected, the peak heights change for the 80% EPDM/20% PP blend as shown in Figure 13. The peak of the rubber phase has been increased, while the peak for the PP is barely visible.

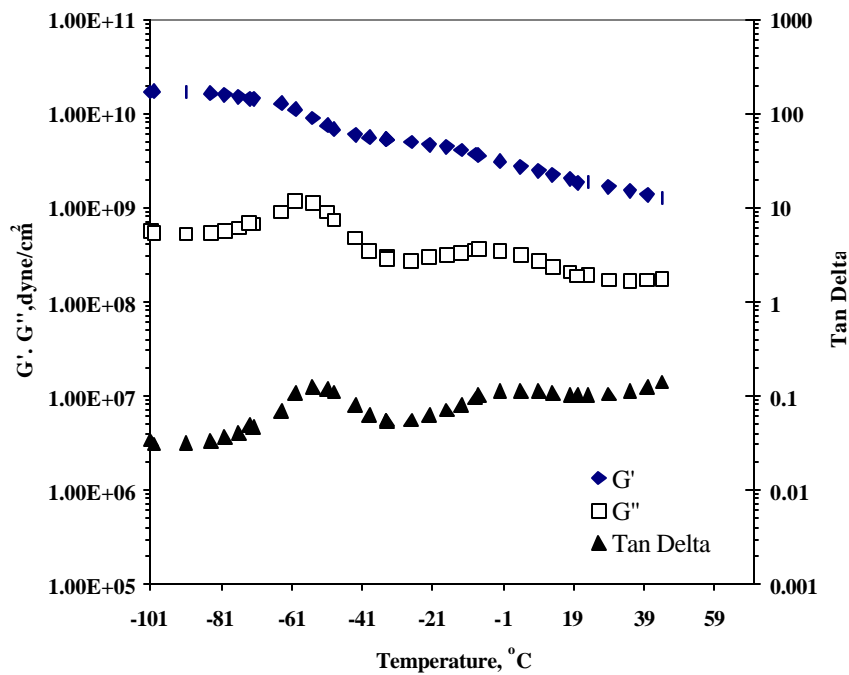


Figure 12. Dynamic mechanical analysis of EPDM/PP blend (50/50% by weight)

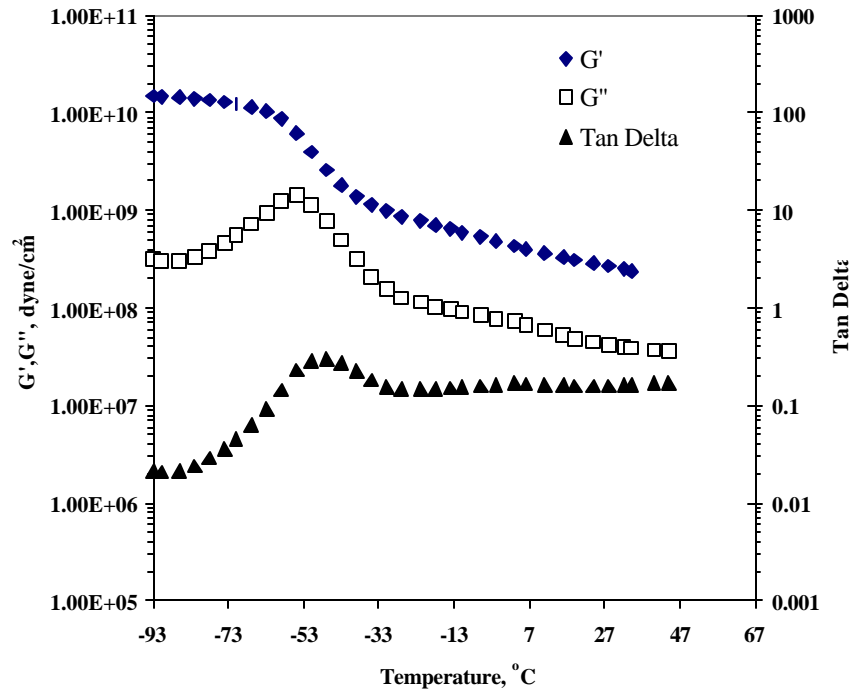


Figure 13. Dynamic mechanical analysis of EPDM/PP blends (80/20% by weight)

5.1.3. Compatibilization Techniques

Two techniques were used to make the rubber and PP compatible: (1) pretreating the rubber and blending it with maleated PP and regular PP and (2) reactive blending.

The surface of the rubber particle was pretreated to generate the hydroxyl groups. This is shown in Figure 14 where an oxidative surface treatment with KMnO_4 solution was used to introduce the hydroxyl group by breaking the double bond at the particle surface. The maleated PP reacts with a hydroxyl group on the rubber surface, attaching the PP chains to the rubber particle. The rubber's surface would then be covered with maleated PP, which is more compatible with regular PP.

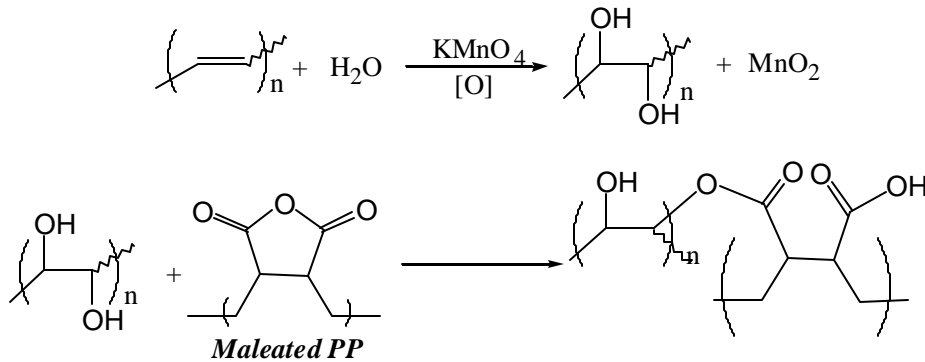


Figure 14. Surface treatment of rubber particle and reaction with maleated PP

The other technique is reactive blending, where double bonds in the rubber particle can be crosslinked by vulcanization agents. Ninety percent of the double bonds in the polymer are still available even after the rubber is vulcanized. Therefore, by adding appropriate grafting agents, those double bonds can be used to graft PP on to the rubber particle surface. Reactive blending with a high rubber-content blend may also promote crosslinking between rubber particles. In any case, the blends produced are expected to show better properties. A peroxide radical initiator, *t*-butyl hydroperoxide, was chosen for the reactive blending. Figure 15 shows the two possible reactions during reactive blending.

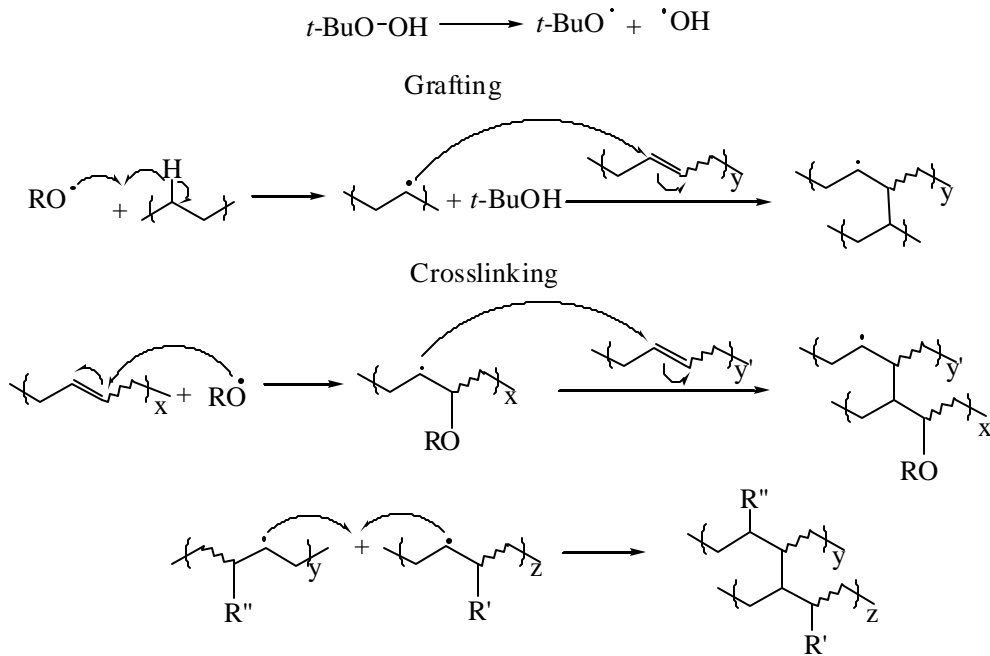


Figure 15. Possible reactions during reactive blending

The ultimate tensile strengths of the blends using these two techniques are compared with the pure rubber/PP blends in Figure 16. Three observations are worth noting. First, the ultimate tensile strength decreases with increasing rubber content. Secondly, the ultimate tensile strength values for the blends using both compatibilization techniques are similar at every rubber concentration. Most importantly, both blending techniques achieved better results than the straight rubber/PP blends.

Figure 17 shows the ultimate elongation results for the blends. Both compatibilization techniques gave much better results than the pure blends. Comparing the two techniques, we can see that the elongation results are similar with up to 40% rubber content. Above 40% rubber content, the reactive blending shows better results with 100% elongation at 50% rubber content and 110% elongation at 80% rubber content.

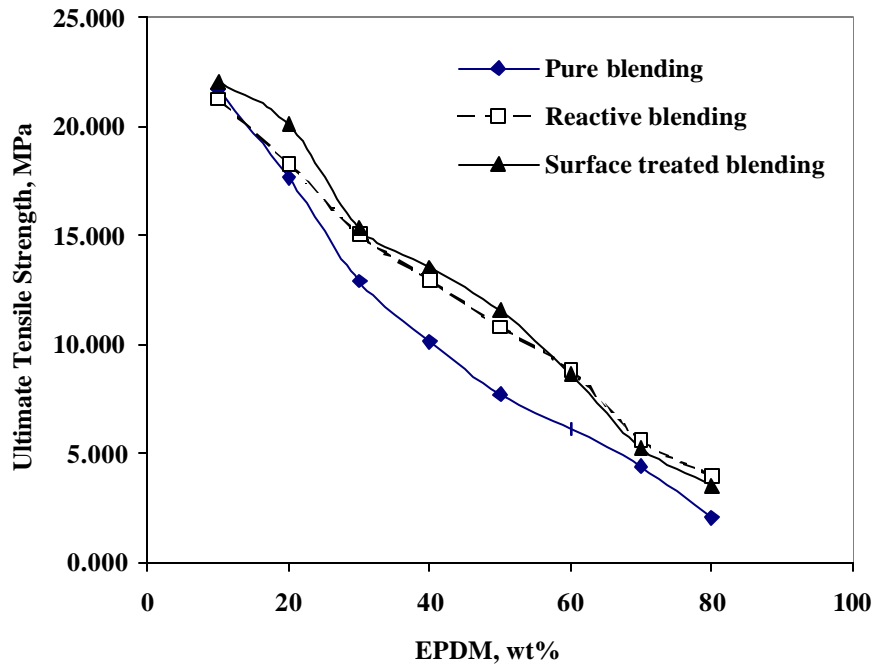


Figure 16. Ultimate tensile strength of EPDM/PP blends

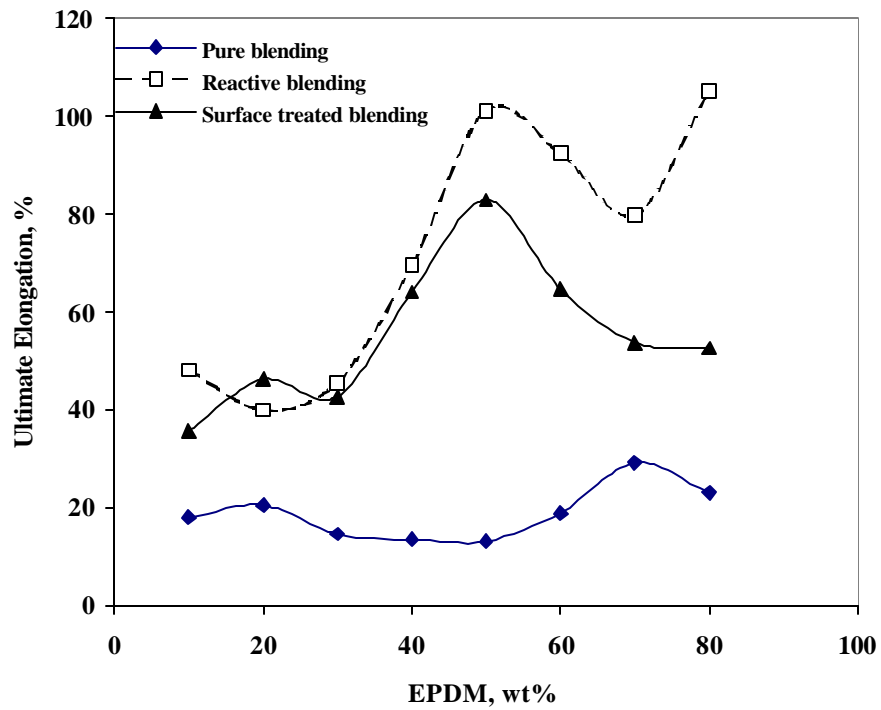


Figure 17. Ultimate elongation of EPDM/PP blends

5.1.4. Identification of Optimum Blending Conditions

In addition to the amount and type of materials, the processing conditions can also affect the blend properties. To determine the optimum blending conditions, experiments on the processing conditions and variables was performed. Six factors with two levels were investigated in EPDM/PP blending. The factors and the designed experimental conditions are shown in Table 7 and Table 8.

Table 7. Controlled Factors and Levels in Experimental Design

Factors	Low	High
Blending Temperature (a)	190°C	220°C
Blending Screw Speed (b)	30 rpm	60 rpm
Blending Time (After the Addition of Rubber) (c)	2 min	6 min
wt% of Peroxide with Respect to Rubber (d)	0.5%	1%
Rubber Particle Size (e)	80 mesh	170 mesh
MFI of PP (f)	0.45 g/10min	12 g/10min

Table 8. Quarter-replicate Factorial Experiment Design

Factors Changed from Condition (1)	Blending Temperature (°C)	Blending Screw Speed (rpm)	Blending Time/Min (After the addition of rubber)	Wt% of Peroxide with Respect to Rubber	Rubber Particle Size (mesh)	MFI of PP (g/10 min)
(1)	190	30	2	0.5	80	0.45
abc	220	60	6	0.5	80	0.45
bd	190	60	2	1.0	80	0.45
acd	220	30	6	1.0	80	0.45
ae	220	30	2	0.5	170	0.45
bce	190	60	6	0.5	170	0.45
abde	220	60	2	1.0	170	0.45
cde	190	30	6	1.0	170	0.45
abf	220	60	2	0.5	80	12.00
cf	190	30	6	0.5	80	12.00
adf	220	30	2	1.0	80	12.00
bcdf	190	60	6	1.0	80	12.00
bef	190	60	2	0.5	170	12.00
acef	220	30	6	0.5	170	12.00
def	190	30	2	1.0	170	12.00
abcdef	220	60	6	1.0	170	12.00

Tensile tests were initially used as the evaluation criteria for the blending. The test results are presented in Table 9. Ultimate tensile strength results showed that none of these factors or the interaction between these factors had a large influence on the ultimate tensile strength.

Table 9. Ultimate Tensile Strength and Elongation Result from Experimental Design

Code	Ultimate Tensile Strength (MPa)		Ultimate Elongation		Factor
	Result	Mean Effect	Result (%)	Mean Effect	
(1)	8.005	15.760	129.314	160.087	
abc	7.462	-0.043	74.671	-12.692	C
bd	8.000	0.124	94.885	-2.264	D
acd	8.014	0.327	88.392	16.066	CD=BF
ae	7.717	0.502	163.048	33.181	E
bce	7.047	0.155	97.728	-0.339	CE=AF
abde	7.858	-0.159	144.521	-0.539	DE=AB
cde	6.822	-0.302	122.698	-1.772	CDE
abf	7.797	0.528	29.508	-68.727	F
cf	6.686	0.516	23.768	24.377	CF=AE=BD
adf	7.109	0.008	24.812	1.302	DF=BC
bcdf	7.957	0.280	42.273	-6.846	B=CDF
bef	8.494	1.011	60.348	-2.002	EF=AC
acef	9.335	0.449	71.018	6.163	A=CEF
def	8.231	-0.001	44.680	-7.327	DEF
abcdef	9.542	-0.071	69.030	-0.608	CDEF=AD=BE

The most important factor controlling the tensile property was the melt flow of PP. That is, the higher the melt flow for the PP, the lower the elongational capability. A possible explanation could be the crystallinity of the PP. The higher the melt flow of PP, the higher the molecular weight and potentially lower crystallinity, with the resulting higher elongation due to the greater amount of amorphous material.

The second important factor is the size of the rubber particle. The smaller the particle size is, the larger the contact surface area will be, resulting into better elongational capability. Particle size has a pronounced effect on mechanical properties, which has been shown in the work of Coran and Patel. As the particle size is decreased, ultimate elongation and tensile strength increase rapidly.¹⁹

The third important factor is the blending time. An increase in blending time decreases the tensile strain. This is probably because shorter blending times lead to less possibility of rubber aging and material degradation.

5.1.5. Influence of the MFI of the PP

As concluded previously, the two most important factors influencing the mechanical properties of the blends are the MFI of the PP and the rubber particle size. Hence, a further investigation of the influence of MFI of the PP was performed by preparing blends using different MFI of PP and untreated EPDM rubber.

As seen in Figure 18, variation in the MFI of the PP shows little influence on the ultimate tensile strength. The tensile strength value varies within 5 MPa in both 50% and 80% rubber content. However, the MFI of the PP shows considerable influence on the ultimate elongation. As seen in Figure 19, a decrease in the MFI results in an increase in the ultimate elongation. By changing the MFI of the PP from 12 to 0.45 MFI, an increase of more than two orders of magnitude in the ultimate elongation values were observed for both 50% and 80% rubber contents.

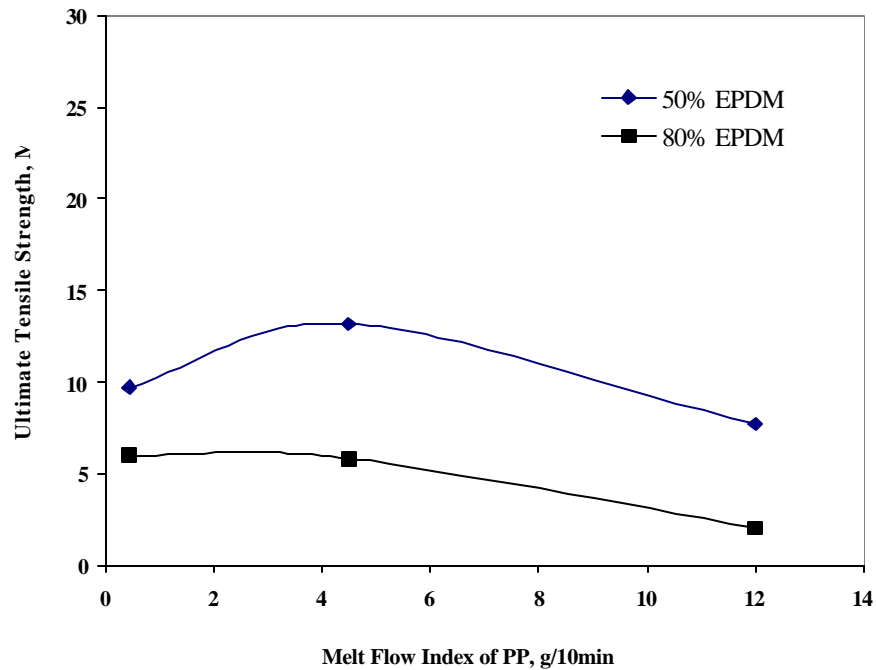


Figure 18. Influence of MFI of PP on ultimate tensile strength

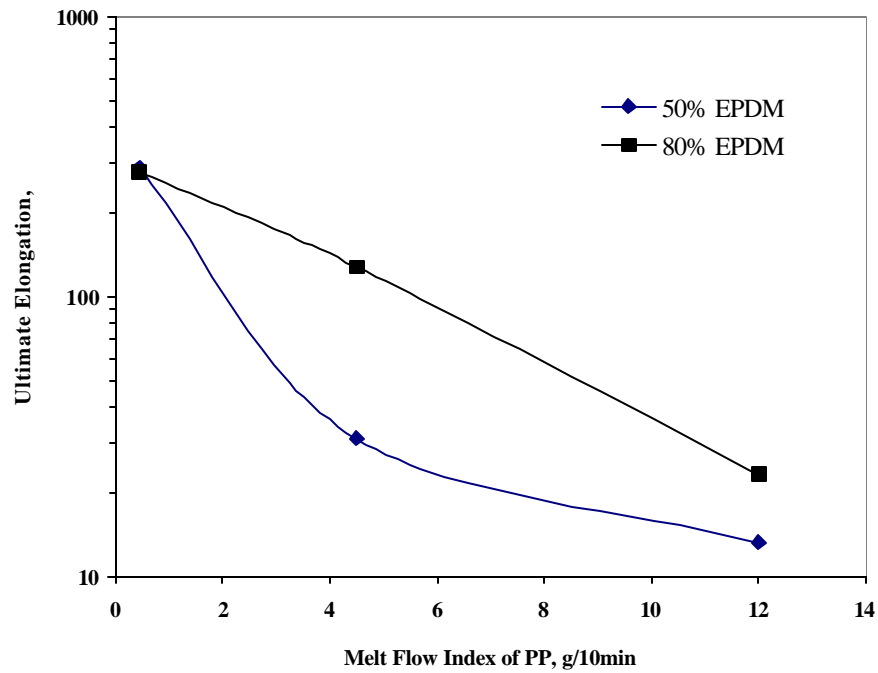


Figure 19. Influence of MFI of PP on ultimate elongation

5.1.6. Size of the Rubber Particles

The studies on the effect of rubber particle size show that similar ultimate tensile strength values were obtained using two different mesh sizes as shown in Figure 20 for 50% EPDM rubber content. As shown in Figure 21, the ultimate elongation value exhibits a slight increase when the mesh size increases (producing smaller rubber particle size). However, the MFI of the PP has a greater influence on these blends. As mentioned above this is similar to results found in other studies.²⁰

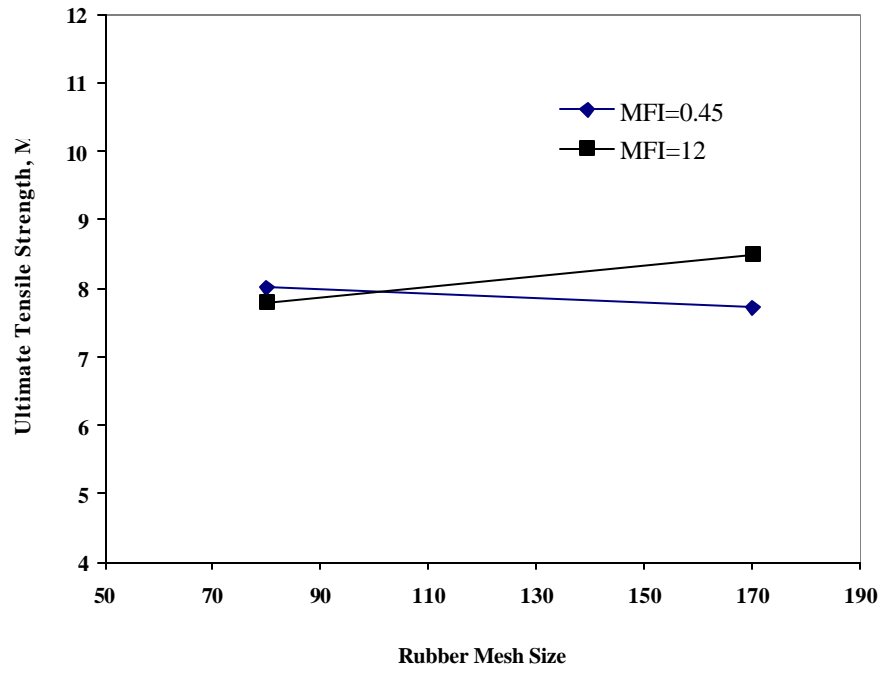


Figure 20. Influence of rubber particle size on ultimate tensile strength

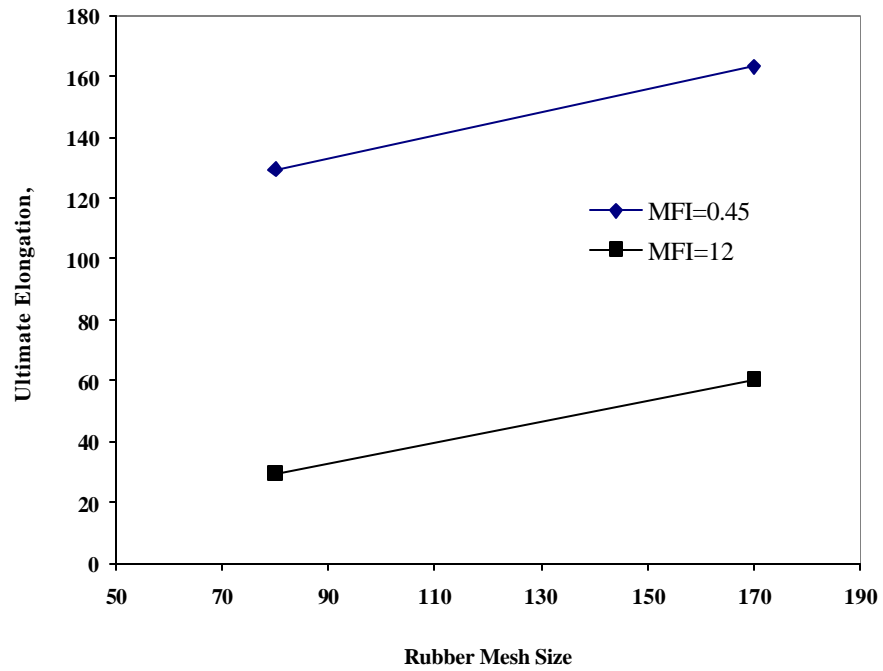


Figure 21. Influence of rubber particle size on ultimate elongation

5.1.7. Effect of the Thermoplastic Base Material (Ethylene-octene copolymer and PP)

The choice of the thermoplastic material can affect the properties of the blend. There are two reasons for this. First, the base properties of the thermoplastic are different and second, the choice can affect the compatibility of the two materials. Since compatibility is important to blend properties, plastic materials that have similar structure and polarity to EPDM can improve the results.

Ethylene-octene copolymer (Engage 8100) was chosen to blend with the recycled EPDM rubber. The resulting ultimate tensile strengths, as shown in Figure 22, show a slight improvement over the PP/EPDM blends (0.45 MFI). The ultimate elongation of the ethylene-octene copolymer blend, shown in Figure 23, shows a dramatic improvement over that of the PP/EPDM blend. The ultimate elongation of the ethylene-octene copolymer blends is higher than that of the ethylene-octene copolymer alone (900%).²¹

These results can be attributed to the structure of the thermoplastic component. Unlike PP, the ethylene-octene copolymer has a lot of short side chains, which leads to only 5% crystallinity in the pure ethylene-octene copolymer. Pure PP would be expected to have higher crystallinity and hence lower elongational capability.

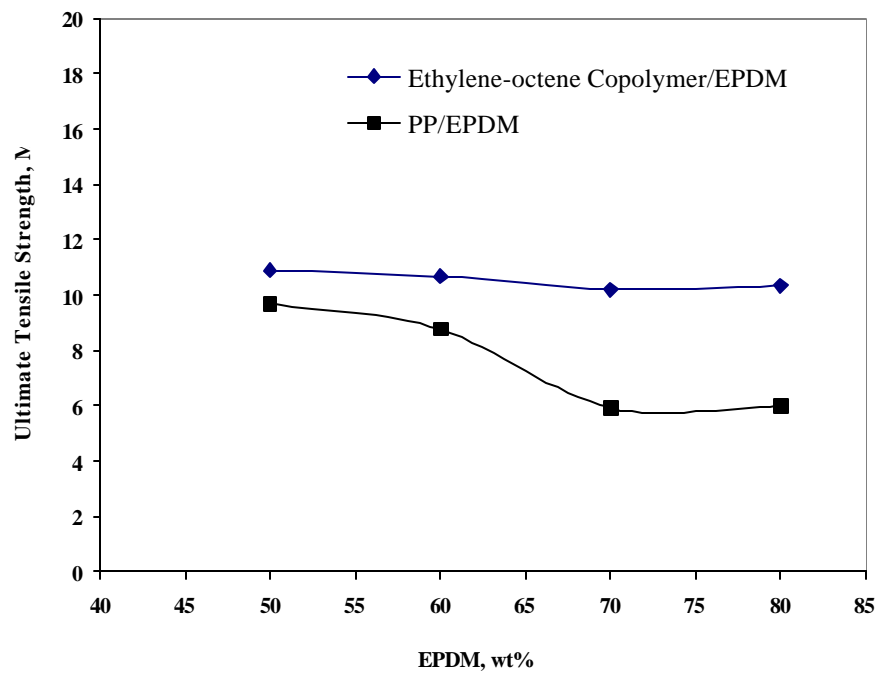


Figure 22. Ultimate tensile strength of EPDM rubber blends

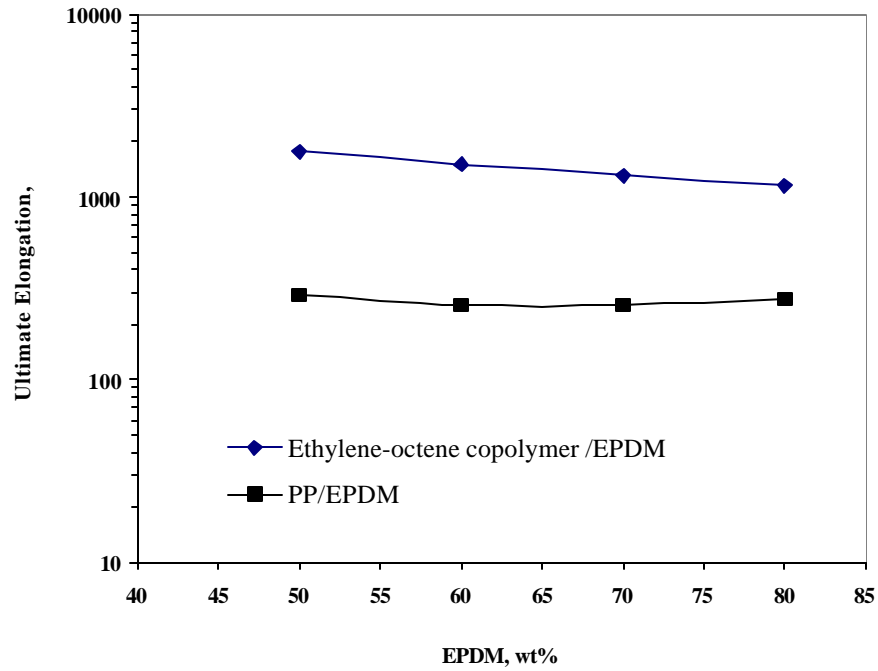


Figure 23. Ultimate elongation of EPDM rubber blends

5.1.8. Effect of the Rubber Material (EPDM and SBR)

Similar blending and tests were performed on blends of PP and SBR rubber with 4.5 MFI PP. A comparison of these two blends, specifically the PP/EPDM blends and the PP/SBR blends, is presented in Figures 24-27.

The DMA results for the PP/SBR are similar to those for the PP/EPDM blends as shown in Figures 24 and 25. Two peaks, representing the existence of the rubber phase and the PP phase, are seen in both 50% and 80% rubber blends. As expected the peak heights change for the 80% SBR/20% PP blend. The peak of rubber phase has been increased while the peak for the PP is barely visible.

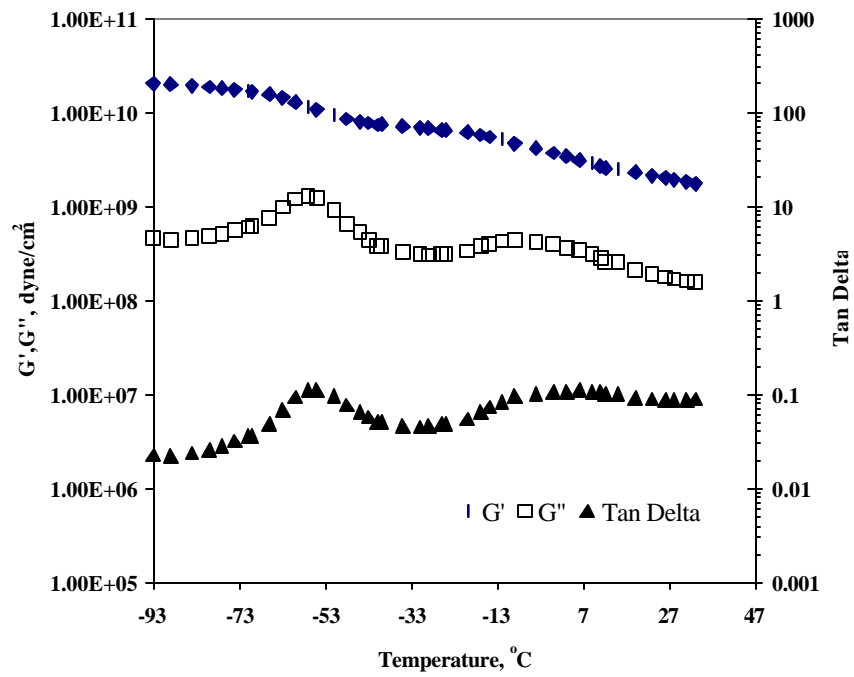


Figure 24. DMA Curve for SBR/PP (50/50 blend)

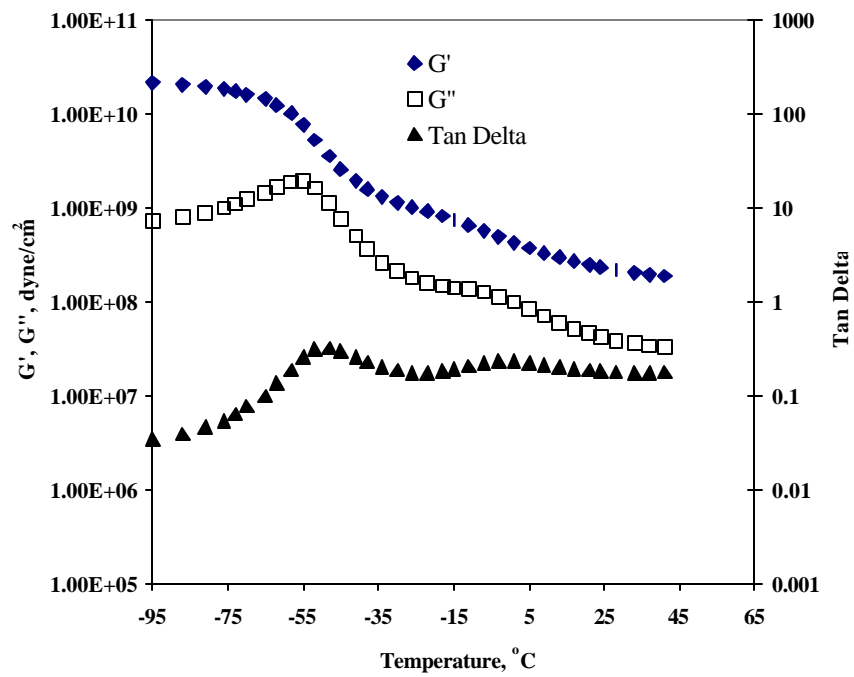


Figure 25. DMA curve for SBR/PP (80/20 blend)

The ultimate tensile strength and the ultimate elongation for the PP/SBR blends are lower than those for the PP/EPDM blends. Furthermore, when the rubber content exceeds a certain point, specifically 70%, no obvious change in the ultimate strength was shown, possibly indicating less compatibility between the PP and the rubber particles in the PP/SBR blend than in the PP/EPDM blend.

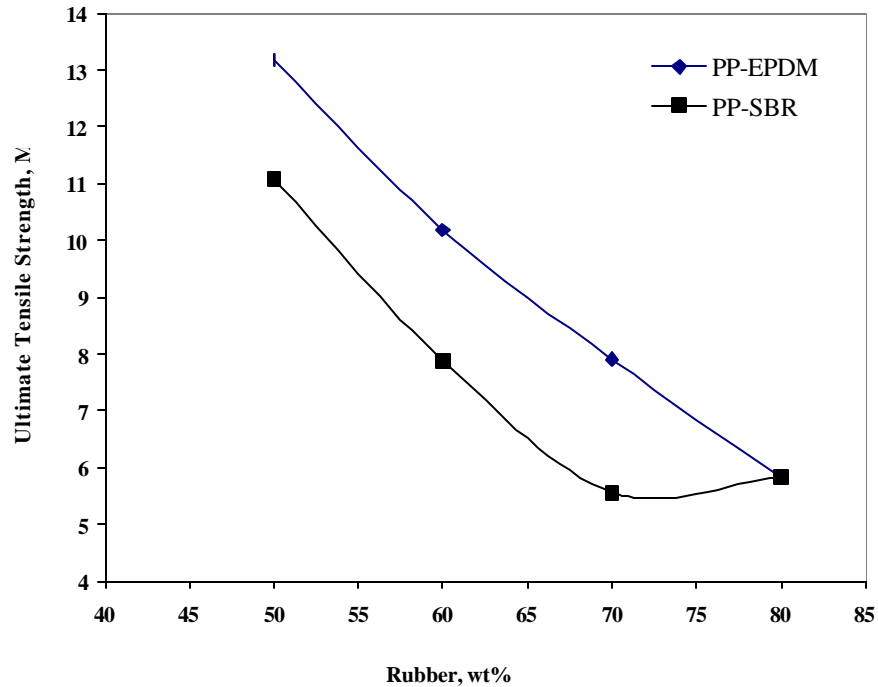


Figure 26. Ultimate tensile strength of rubber/PP blends

It is important to note that the ultimate elongation of the PP/SBR system is much smaller than that of the PP/EPDM blend. As seen in Figure 27, the elongation of the PP/SBR varies slightly around 40%, while that of the PP/EPDM shows a bell-shaped curve, with a maximum elongation of 300% at a rubber content of 65%.

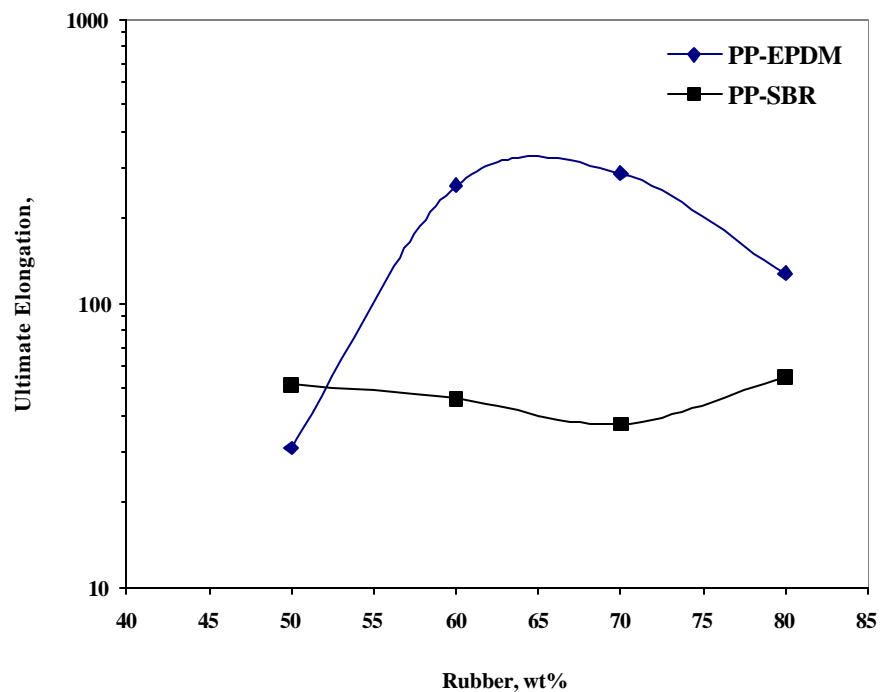


Figure 27. Ultimate elongation of rubber/PP blends

Testing was also performed on blends of SBR rubber with 12 MFI PP. The results from these blends were compared to commercially available sports surface materials. The results are shown in Table 10 and 11.

Table 10. Testing Results for Recycled SBR/PP Blends

% SBR	Tensile (MPa)	Elongation (%)	Hardness Shore A
40	12.2	16.2	96
50	8.5	36.1	93

Hardness of recycled SBR/PP blends decreases with increasing percentages of recycled SBR. Similar to the results for the EPDM rubber, this decrease in hardness is due to the lower T_g of the recycled SBR. This lower T_g makes the rubber softer or more flexible. Therefore, as the recycled SBR content is increased, the hardness is decreased.

A comparison of recycled EPDM/PP blends and recycled SBR/PP blends can be found in Table 11 for 12 MFI PP. The results in Table 11 show that the two recycled rubbers have similar physical properties at similar percentages in blends with PP.

Table 11. Comparison of Recycled Rubber/PP Blends

% Rubber	10	20	30	40	50	60	70	80
EPDM Tensile (MPa)	21.7	17.7	12.9	10.1	7.7	6.1	4.4	2.0
SBR Tensile (MPa)				12.2	8.5			
EPDM Strain (%)	18.0	20.6	14.6	13.5	13.2	18.8	29.2	23.2
SBR Strain (%)				16.2	36.1			
EPDM Hardness Shore A					96.0	94.0	88.0	84.0
SBR Hardness Shore A				96.0	93.0			

5.2. Market Analysis

5.2.1. Application Areas

There are many possible applications for recycled rubber and PP blends. Two of the more feasible applications are roofing and flooring. These two applications were chosen for investigation because the physical properties of the recycled rubber and PP blends are comparable to that of current commercial products. The flooring application has been more thoroughly researched. The physical properties of commercial flooring were determined via phone conversations and the Internet. Three companies, Advantage Sport USA, Inc., Futura Coatings Inc., and Riviva Rubber, produce commercial flooring. Advantage Sport USA, Inc. produces two forms of commercial flooring under the trade names Uni-Turf and Alpha Sport. Futura Coatings Inc. produces commercial flooring under the trade name Gymflex. Riviva Rubber produces commercial flooring under the trade name Tuflex, which is subcategorized by color patterns under the trade names Spartus and Titan. These sporting surfaces are based on rubber, polyurethane, polyvinyl chloride, or some combination of rubber and polyurethane. Some important physical properties of the manufactured commercial flooring, which can also be used in weight rooms and outdoor running tracks, are listed in Table 12.

Table 12. Physical Properties of Commercial Flooring

Manufacturer	Trade Name	Base Material	Elongation (%)	Hardness Shore A	Tensile (MPa)
Advantage Sport USA	Uni-Turf	Polyvinyl chloride		70+/-5	6.9+/-1.0
Advantage Sport USA	Alpha Sport	Rubber & polyurethane	60 minimum	55	3.0+/-0.7
Futura Coatings	Gymflex	Polyurethane	100+/-10	55-60	0.72
Riviva Rubber	Tuflex	Rubber	118+/-25	60+/-5	8.3+/-0.8

Three physical properties, percent elongation, hardness, and tensile strength, were very significant to the specific surfacing needs of the clientele of the three companies noted above. Those three properties in the blends and the commercial materials were evaluated and compared in Table 13. The blends use 12 MFI PP and either EPDM rubber or SBR rubber.

Table 13. Properties Comparison of Experimental Blends and Commercial Products

Material	Hardness (Shore A)	Tensile Strength (MPa)	Elongation (%)
Uni-Turf	70+/-5	6.9+/-1.0	170
60% EPDM (170)	94	6.1	19
50% SBR (80)	93	8.5	36
Alpha Sport	55	3.0+/-0.7	60
70% EPDM (170)	88	4.4	29
50% SBR (80)	93	8.5	36
Gymflex	57+/-3	0.7	100+/-10
80% EPDM (170)	84	2.0	23
50% SBR (80)	93	8.5	36
Tuflex	60+/-5	8.3+/-0.8	118+/-25
70% EPDM (170)	88	4.4	29
50% SBR (80)	93	8.5	36

A comparison of physical properties shows the experimental blends could possibly meet or exceed the necessary requirements. Some of the physical properties of the blends require some improvement when compared to the properties of the commercial flooring. The commercial materials have a slight advantage over the experimental blends in Shore A hardness and percent elongation. The difference between hardness test results for the different recycled rubber percentages in the blends was small. The experimental blends are considered competitive, and in some cases, stronger than the commercial flooring with regards to the tensile strength.

The information found in the tables above shows that the experimental blends of recycled rubber and PP are competitive in physical properties compared to four currently marketed commercial sports surfaces. Because the product has low-end performance requirements, the cost of the product is an important consideration.

5.2.2. Cost Analysis

The price of the overall product is a function of both machine and material costs. These experiments were conducted on lab scale machinery, not the more efficient large-scale commercial machines a manufacturer would use. Variations in the material costs for the product are based on two factors: the use of recycled PP versus virgin PP and the use of 170 mesh recycled rubber.

The price comparison of recycled PP versus virgin PP can be seen in Table 14. General Polymers²² quoted the virgin PP cost. U.S. Polymers²³ quoted the recycled PP cost. The virgin material can be compared to the recycled material by the use of averages and ratios. Figure 28 compares the average costs of virgin PP and recycled PP through the use of a factor.

Table 14. Price Comparison of Virgin and Recycled PP

Material (kg)	Virgin (\$)	Recycled (\$)	Difference (\$)
675	\$1.04	\$0.23	\$0.81
1125	\$0.84	\$0.23	\$0.61
3000	\$0.79	\$0.20	\$0.60
5000	\$0.70	\$0.20	\$0.51
8000	\$0.66	\$0.20	\$0.47
13650	\$0.65	\$0.18	\$0.47
35000	\$0.64	\$0.18	\$0.46

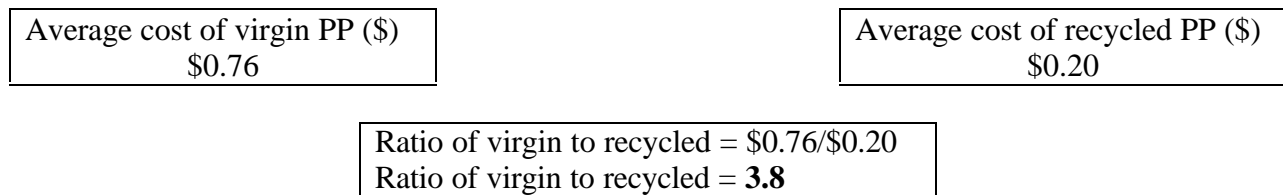


Figure 28. Calculation of average cost ratio of virgin to recycled PP

The virgin material is more expensive on average than the recycled material by a factor of 3.8. This can translate into a major cost savings in the overall product, based on the experimental blend.

The second factor in the material cost of the experimental blends is the use of 170 mesh versus 80 mesh for the particle size of the recycled rubber. The cost of the recycled rubber is based on particle size alone; the material, whether it is EPDM or SBR, is not a factor in the price. The cost comparison of the recycled rubber for different mesh sizes can be found in Table 15.

Table 15. Cost Comparison of Mesh Size for Recycled Rubber

Material (kg)	170 Mesh	80 Mesh	Difference (\$)
2250	\$0.75	\$0.43	\$0.32
4500	\$0.72	\$0.38	\$0.34
9000	\$0.70	\$0.35	\$0.35
18000	\$0.65	\$0.33	\$0.32

Erickson Materials²⁴ quoted the prices found in Table 15. The 170 mesh is a smaller particle size. Therefore, the 170 mesh recycled rubber is more expensive because of increased grinding time and alternate grinding methods. The 170 mesh material can be compared to the 80 mesh material

by use of averages and ratios. Figure 29 below compares the average costs of 170-mesh recycled rubber and 80-mesh recycled rubber through the use of a factor.

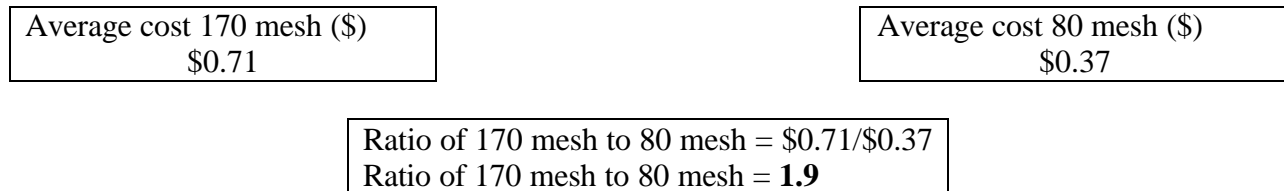


Figure 29. Calculation of average cost ratio of 170 mesh to 80 mesh recycled rubber

The 170 mesh or smaller particle size is more expensive on average than the 80 mesh, or larger particle size, by a factor of 1.9. This can also translate into significant cost savings in the overall product.

Overall, the use of recycled PP or virgin PP is a more significant factor than the use of 170-mesh recycled rubber or 80-mesh recycled rubber. This can be directly related to the average cost ratio of the two materials. The ratio of the PP is 3.8, which is twice the ratio for the different recycled rubbers, which is 1.9.

A commercial scale operation would not only reduce material costs due to bulk purchasing, but would also reduce the amount of labor and/or machine power used. The scale-up version of blends as compared to the laboratory scale can be found in Table 16.

Table 16. Commercial Scale Recycled Blends vs. Laboratory Scale

	Laboratory Scale	Commercial Scale
Weight	g	kg
Blending	Lab mixer	Twin or single screw extruder
Grinding	Lab mill	None required
Formation	Compression mold	Sheet die

Table 16 shows the elimination of the grinding and the formation as separate processes. The possible elimination of these steps would result in cost savings from both a labor and machine standpoint. The twin or single screw extruder, with a simple sheet die, will perform the task of blending and forming the flooring in one continuous step. The twin screw extruder may require the addition of a gear pump before the sheet die. The recycled blend would exit the sheet die and be wound onto spools. The spools would facilitate the installation of the flooring. The only material handling that would be required is the removal of the spools when full and the supervision of the extruder. The power required for this operation will be higher than the laboratory scale operation. These scale-up factors will be a significant source of savings. The scale-up costs can be estimated by using the cost of materials and the power law formula shown in equation (1).

$$(C_a/C_b) = (S_a/S_b)^x \quad (1)$$

where C_a is the cost of a, S_a is the size of a, x is the exponent, C_b is the cost of b, and S_b is the size of b. As previously discussed, the power law or exponential factor (x) commonly ranges from 0.6-0.8. Because of the roughness of the estimate, which is based on material cost only, an overestimate is in order. The overestimate will be used to cover other costs such as machinery, power, and labor. Because of the significance of these additional unknown costs, the exponent chosen (1.1) was almost double what is commonly used. In order to solve the equation a sample surface, e.g., a basketball court, is needed. Table 17 solves the power law for the experimental blend of a 50% 80-mesh recycled rubber and 50% virgin PP.

Table 17. Material Costs and Inputs

Materials		Material Cost	
percentage SBR	50	cost of virgin PP	\$1.04 per kg
percentage PP	50	cost of recycled 80 mesh SBR	\$0.43 per kg
Laboratory Scale Sheet		cost of PP in blend	
Experimental sheet size		\$1.04 x 0.045 = \$0.05	
9.0cm x 12.5cm x 0.15cm = 0.01125m² = S_a		cost of SBR in blend	
weight of experimental sheet		0.015kg	
0.015kg		\$0.43 x 0.045 = \$0.02	
Laboratory Scale Sheet Cost		Size of Application	
total experimental blend cost		dimensions of basketball court	
\$0.05 + \$0.02 = \$0.07 = C_a		15.25m x 25.5m = 390m² = S_b	
Scale Up Values			
corrected sheet size		9.0cm x 12.5cm x 0.9cm	
weight correction for thickness		0.09kg	
weight of recycled 80 mesh SBR		0.09g x 0.50	
weight of recycled 80 mesh SBR		0.045kg	
weight of virgin PP		0.09g x 0.50	
weight of virgin PP		0.045kg	

The variables calculated in Table 17 are now placed in the power law equation in Table 18.

Table 18. Power Law Calculation

$C_a = \$0.07$	$(C_a/C_b) = (S_a/S_b)^x$
$C_b = ?$	$(C_a/C_b) = [(\$0.07)/(C_b)]$
$S_a = 0.01125m^2$	$(S_a/S_b)^x = [(0.01125m^2)/(390m^2)]^{1.1}$
$S_b = 390m^2$	
$X = 1.1$	$C_b = \$6,902.42$

The experimental sheet is only 0.15 cm thick; however most commercial flooring is 0.9 cm thick. Therefore there is a correction factor of 6, which is multiplied by the thickness and weight of the experimental sheet. The final estimate for the cost of surfacing a basketball court with the experimental blend is \$6,902.42. This overestimate should cover any costs that were left out or overlooked. An example of how the commercial flooring was priced for a basketball court can be found in Table 19.

Table 19. Calculation of Commercial Flooring Cost for Basketball Court

basketball court area	390m ²
Spartus or Titan tile area	0.5m ²
cost of Spartus per tile	\$22.60
cost of Spartus per m ²	\$45.20
cost of Titan per tile	\$16.80
cost of Titan per m ²	\$33.60
cost of Spartus basketball court	(390m²)(45.20\$/m²) = \$17,628
cost of Titan basketball court	(390m²)(33.60\$/m²) = \$13,104

The power law was used for cost analysis of three different courts (basketball, tennis and roller hockey) for four different blends. The cost comparison takes into account the percentage of rubber or PP used in the experimental blend, the exponential factor for a scaled-up process, and the overall area of the specific court. The comparison also accounts for the cost of virgin PP and 170-mesh or 80-mesh recycled rubber. The cost comparison of the commercial product versus experimental blends can be found in Table 20.

Table 20. Price Comparison of Commercial Product and Experimental Blends

Basketball					
Blend	C _b	Spartus	Spartus Savings	Titan	Titan Savings
80%EPDM (170)/20%PP(V)	\$6,901.99	\$17,628.00	\$10,726.01	\$13,104.00	\$6,202.01
70%EPDM (170)/30%PP(V)	\$7,887.99	\$17,628.00	\$9,740.01	\$13,104.00	\$5,216.01
60%EPDM (170)/40%PP(V)	\$7,887.99	\$17,628.00	\$9,740.01	\$13,104.00	\$5,216.01
50%SBR (80)/50%PP(V)	\$6,901.99	\$17,628.00	\$10,726.01	\$13,104.00	\$6,202.01
Tennis					
Blend	C _b	Spartus	Spartus Savings	Titan	Titan Savings
80%EPDM (170)/20%PP(V)	\$12,517.43	\$30,284.00	\$17,766.57	\$22,512.00	\$9,994.57
70%EPDM (170)/30%PP(V)	\$14,305.64	\$30,284.00	\$15,978.36	\$22,512.00	\$8,206.36
60%EPDM (170)/40%PP(V)	\$14,305.64	\$30,284.00	\$15,978.36	\$22,512.00	\$8,206.36
50%SBR (80)/50%PP(V)	\$12,517.43	\$30,284.00	\$17,766.57	\$22,512.00	\$9,994.57
Roller Hockey					
Blend	C _b	Spartus	Spartus Savings	Titan	Titan Savings
80%EPDM (170)/20%PP(V)	\$38,484.80	\$84,072.00	\$45,587.20	\$62,496.00	\$24,011.20
70%EPDM (170)/30%PP(V)	\$43,982.63	\$84,072.00	\$40,089.37	\$62,496.00	\$18,513.37
60%EPDM (170)/40%PP(V)	\$43,982.63	\$84,072.00	\$40,089.37	\$62,496.00	\$18,513.37
50%SBR (80)/50%PP(V)	\$38,484.80	\$84,072.00	\$45,587.20	\$62,496.00	\$24,011.20

(V) represents virgin PP used in the blend.

(80) and (170) represent the mesh size of the rubber used in the blend.

Spartus and Titan are trade names for commercial flooring materials produced by Riviva Rubber. These two materials were price quoted for the three courts in the same manner as in Table 19.

The four material blends (80% EPDM, 70% EPDM, 60% EPDM and 50% SBR), which can be found on the left side of Table 20, represent the most competitive experimental blends with regards to both cost and physical properties. Although the physical properties are not equal, the cost savings are significant enough to make the experimental blends very competitive in an open market.

Table 21. Ratio Comparison of Experimental Blends Costs to Commercial Costs

Basketball		
	80%EPDM & 50%SBR	70%EPDM & 60%EPDM
Spartus	2.55	2.23
Titan	1.90	1.66
Tennis		
	80%EPDM & 50%SBR	70%EPDM & 60%EPDM
Spartus	2.42	2.12
Titan	1.80	1.57
Roller Hockey		
	80%EPDM & 50%SBR	70%EPDM & 60%EPDM
Spartus	2.18	1.91
Titan	1.62	1.42

The cost ratios are summarized in Table 21, which shows that the commercial product is from 1.42 to 2.55 times the estimated price of the experimental blends. This large cost savings should overshadow any inconsistencies in the physical properties of the experimental blends.

These results were obtained on the simple blends with 12 MFI PP. Additional work using other MFI PP grades has not been compared to commercial compounds and would be expected to show better properties. It is also possible to use additives or other techniques to improve the elongation and hardness of the experimental blends. These additives were discussed earlier in the blend development section, but the properties were not compared to commercial materials. Although these additives will increase the price of the product, the overall cost savings and overestimate in the power law factor should make these additives cost-competitive.

6. Conclusions

This work has looked at methods to blend ground scrap rubber and thermoplastics into new and useful materials. The recycled ground rubber was blended with PP to form a new material that can be used in applications such as sports surfaces. In addition, this new material is easily recycled simply by heating it. In essence, the work has converted a thermoset material into a thermoplastic that can be reused and converted into new products simply by reheating the material and forming it into a shape in much the same manner as other thermoplastics.

A variety of blends were prepared to determine the effect of rubber particle size, MFI of the PP, percentage of rubber by weight, and type of thermoplastic on the blend's physical properties. In addition, several blend compatibilization techniques were developed. As a result of these investigations, the MFI of the PP was determined to be a key factor in the mechanical properties of the blends. By proper selection of the components and compatibilization techniques, the blends can be tailored for specific applications. The results of this work can be used to guide manufacturers in the proper selection of materials and techniques to use recycled rubber in blends for a variety of product applications.

An investigation of possible applications for these blends was performed and several areas were targeted, including sports surfaces. The physical properties of some of the blends were compared to commercial products through the use of experimental testing, such as tensile strength, percent elongation, and hardness. The physical properties of these experimental blends have been shown to compete with commercial sports surfacing and flooring. The cost factors for a scaled-up operation to manufacture the experimental blends have been discussed and the experimental blends were shown to be cost-competitive in the open market through the use of the power law equation.

7. Recommendations

Further work should investigate methods to improve the compatibility of the SBR and PP blends. The use of recycled PP should also be researched. Recycled PP can be readily purchased and the effectiveness of recycled PP versus virgin PP should be determined. The cost effectiveness of recycled PP has already been shown briefly in this study. In addition, a comparison of all of the different blends with the commercial flooring applications should be performed. Finally, based on the information obtained in this phase of the work, a scale-up study should be performed for a specific application. This should allow the technology to be transferred to a manufacturer in a more efficient manner.

8. References

- ¹ Rosenberg, S, Tire recycling initiative speech p. 2.
- ² M. Blumenthal, *BioCycle* 53 (October 1997).
- ³ Rosenberg, S, Tire recycling initiative speech p. 2.
- ⁴ Mullins L, *Natural Rubber Technology* 1971 Vol.3.
- ⁵ N. Whetten, J. Weaver, D.N. Humphrey and T. Sandford "Rubber Meets the Road in Maine," *Civil Engineering*, 67 (9), 60 (1997).
- ⁶ Rosenberg S, Tire recycling initiative speech.
- ⁷ ITRA's Tire and Rubber Advisory Council. 1998 Tire and rubber industry: leading a dynamic lifestyle pp.3.
- ⁸ M. Pittolo and R.P. Burford, *Rubber Chemistry and Technology*. 58, 97 (1985).
- ⁹ Goodyear Company.
- ¹⁰ International Tire Recycling Association.
- ¹¹ M. Pittolo and R.P. Burford, *Rubber Chemistry and Technology*. 58, 97 (1985).
- ¹² J. McKirahan, P. Liu, and M. Brillhart, *ANTEC '96*, p. 3110.
- ¹³ A. Chidambaram and K. Min, *ANTEC '94*, p. 2927.
- ¹⁴ Coran, A., *Rubber Chemistry and Technology*, 68, 351 (1995).
- ¹⁵ Park, R., *Cost Engineering Analysis*, John Wiley & Sons, New York, 1984, pp.130-133.
- ¹⁶ Ostwald, P., *Cost Estimating for Engineering and Management*, Prentice-Hall, New Jersey, pp. 201-202.
- ¹⁷ R. P. Burford and M. Pittolo, *Rubber Chemistry and Technology*, 55, 1233 (1982).
- ¹⁸ Data Sheet from Erickson Materials, Inc.
- ¹⁹ Coran, A., *Rubber Chemistry and Technology*, 68, 351 (1995).
- ²⁰ Coran, A., *Rubber Chemistry and Technology*, 68, 351 (1995).
- ²¹ Engage Data Sheet, DuPont-Dow Elastomer.
- ²² General Polymers, 59 Foundry Street, Central Falls, RI 02863.
- ²³ General Polymers, 59 Foundry Street, Central Falls, RI 02863.
- ²⁴ Erickson Materials, 4 H Gill Street, Woburn, MA 01801.