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Mechanical and Tribological Properties of Composites of Recycled High Density Polyethylene and Recycled Rubber

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Jason G. Boulanger

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Abstract:

This thesis presents a study on the mechanical and tribological properties of composite materials of recycled high density polyethylene (HDPE) and recycled rubber tire particles. The materials were compounded by extrusion and formed into test specimens by injection molding.

The first experiment studied the effect of recycled rubber percentage on mechanical properties of composites of recycled HDPE and recycled rubber. The mechanical properties included tensile strength, percent elongation, hardness, and impact resistance. Recycled rubber concentrations of 0, 5, 10, 15, 20, 25, and 30 percent were tested. The second experiment investigated the tribological properties of recycled HDPE and recycled rubber composites. Tests were performed on the composite specimens to determine the effects of normal pressure, sliding speed, and recycled rubber percentage on coefficient of friction and wear rate. Normal pressure in the range in the range between 9.87 and 24.60 MPa was applied on specimens containing five percent recycled rubber at a sliding speed of 5.10 m s^{-1}. Sliding speed between 2.55 and 5.95 m s^{-1} was studied on specimens containing five percent recycled rubber at a normal pressure of 16.46 MPa. Rubber percentages of 0, 5, 10, 15, 20, 25, and 30 percent were tested at a normal pressure of 16.46 MPa and a sliding speed of 5.10 m s^{-1}.

Tensile strength decreased as recycled rubber percentage increased for the composites of recycled high density polyethylene and recycled rubber particles. The ductility of the composites decreased drastically as recycled rubber content increased to five percent, and further decreased gradually from five to 30 percent. The hardness decreased as recycled rubber content increased. The impact strength decreased drastically

at five percent recycled rubber. It remained fairly constant from five to 25 percent of recycled rubber, and then decreased as rubber content increased to 30 percent.

The tribological experiments showed that coefficient of friction and wear rate increased as the normal pressure increased for the composite of recycled HDPE with five percent recycled rubber. Coefficient of friction and wear rate increased as the sliding speed increased for composites of recycled HDPE with five percent recycled rubber. Coefficient of friction and wear rate increased as the recycled rubber percentage increased in composites of recycled HDPE with recycled rubber.

Microscopic analysis of the friction and wear test specimens was performed to determine structural changes due to sliding. The sliding surface and cross section of the tested specimen were examined. The results of this analysis showed that surface damage increased as normal pressure, sliding speed, or percentage of recycled rubber increased. The depth of deformation decreased as the sliding speed increased, while the depth increased with increasing normal pressure and rubber percentage.

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CHAPTER I

INTRODUCTION

We generate enormous amount of wastes as we consume various products. In 1994, Americans generated 209 million tons of municipal solid waste (MSW). As the U.S. population grows, along with the variety and amount of commercial products we use, so does the amount of MSW that Americans generate every year. The MSW volume has increased 250 percent since 1960, and is estimated by the U.S. Environmental Protection Agency (EPA) to reach 262 million tons by 2010 (Keep America Beautiful, Inc., 1997a). Landfills currently manage 61 percent of municipal solid waste in the U.S. Unfortunately, 80 percent of all the landfills existing in the United States will be filled to capacity by the year 2009 (Hammond, 1992).

The realization that raw materials are limited in supply, and that landfill space is diminishing, places an increasing push on recycling. Recycling, or making valuable use of trash, is a key to alleviate the solid waste disposal problem. Many types of plastic packaging have come into the market within the past 15 years, and recycling many of these has followed. Today, approximately 15,000 communities, nearly half of the U.S. population, have access to plastic recycling facilities. Since 1989, the amount of plastic packaging recycled in the U.S. has steadily increased and recycling continues to grow. Despite the increased effort of plastics recycling, an estimated 9.5 percent of all landfill space is being occupied by plastics (U.S. Environmental Protection Agency, 1995).

Tires consume 51 percent of the rubber used in the world. Americans generate 250 million scrap tires each year, which is about one tire per capita. Despite significant strides in recovery rates, the EPA has reported that two to three billion scrap auto and truck tires have been either stockpiled or illegally dumped (Keep America Beautiful, Inc., 1997b). The unregulated disposal of these tires has the potential to create environmental and health hazards. Rainwater accumulates in tire stock piles creating an ideal environment for mosquitoes and other insects, which transmit disease to humans.

Another hazard is the tendency for tire piles to catch fire. Tire fires are hard to extinguish, which pollute the air, and cause damage to surrounding communities.

This research was proposed to study the mechanical and tribological properties of the composites made of recycled high density polyethylene (HDPE) with recycled automotive tire particles. The materials were processed by extrusion, and then injection molded into test specimens. With this knowledge, we can promote more practical applications for the recycled materials, thus help alleviate the solid waste problem.

1.1 Statement of Research

The purpose of this research was to study the mechanical and tribological behavior of composites of recycled HDPE with recycled tire rubber. The relationship between process variables, mechanical properties, and friction and wear behavior was studied. Process variables included the percentage of recycled rubber and processing methodology. The mechanical properties included tensile strength, ductility (percent elongation), hardness, and impact resistance. The tribological study included coefficient of friction, and wear rate. The relationship between tribological behavior and material structure was investigated in order to control and improve the properties of the composites. Material structure included distribution of recycled rubber particle within the composite, interfacial bonding between the recycled rubber and recycled HDPE matrix, and the change caused by the sliding process.

1.2 Significance of Research

This research facilitates understanding composites made of recycled materials. Once the properties of the composites are known, the composites can be used as industrial materials. This knowledge will benefit both industry and community as landfilling and incineration become more expensive and less acceptable. As the need for recycling materials grows, so will the appropriate markets and financial support to utilize recovered materials. Ultimately, this will help increase the amount of recycling in communities, and reduce the amount of HDPE and tires entering the waste stream.

1.3 Definitions

The following terms and definitions are essential to the understanding of the research.

1. Extruder/Extrusion - This is a compounding device used to mechanically mix the recycled HDPE and recycled rubber to form a composite material. The extrusion process forces the constituents together by the screw action at operating temperatures. A viscous composite material forms as it exits the extruder die.

2. Coefficient of Friction - The measure of the resistance encountered when one body moves tangentially over another with which it is in contact (Williams, 1994). It is calculated by Equation (1).

$$\mu = F / N \tag{1}$$

where

μ = *Coefficient of friction,*
F = *Frictional force,*
N = *Normal force.*

3. Hardness - A quantitative assessment on the resistance of a material to penetration by indentation. Composites tested during this research was measured according to Durometer hardness type "D" (ASTM D2240).

4. High Density Polyethylene (HDPE) - A thermoplastic polymer produced by reacting incompressible ethylene under reaction conditions. HDPE has a melt temperature range of 110 to 135°C and a density range of 0.941 to 0.965 g/cm^3 (Charrier, 1991).

5. Impact Resistance - The quantitative assessment of the resistance to breakage by flexural shock. The composites tested during this research were measured according to ASTM standard D 256.

6. Injection Molding Machine - This is a compounding and injection device used to mold the recycled HDPE and recycled rubber composite material into ASTM test specimens. The process forces the material into a mold by an injection screw.

7. Municipal Solid Waste - Waste from residential, commercial, institutional, and some industrial sources.

8. Percent Elongation - The percent elongation measures the ductility of a material and indicates the amount of elongation as a result of a tensile test, as in Equation (2) (ASTM D638M).

$$e\% = (L - Lo) / Lo \tag{2}$$

where

$e\%$ = *Percent elongation,*
L = *Final length,*
Lo = *Original length.*

9. Rubber - The rubber used in this research is recycled vulcanized rubber from ground tires. Rubber is vulcanized by the curing of certain chemicals, mainly sulfur, to produce cross-linked carbon to carbon or double bonded carbon molecular chains. Vulcanization temperatures are a function of the chemical reaction during the vulcanization process (Charrier).

10. Tribology - The science and technology of interacting surfaces in relative motion and of related subjects and practices; dealing with every aspect of friction, lubrication, and wear.

11. Ultimate Tensile Strength - A measure of the uniaxial resistance of a material to fracture when being pulled apart during loading (Charrier). It is calculated by Equation (3) (ASTM D638 M).

$$\sigma = P_{max} / A_o \tag{3}$$

where

σ = *Ultimate tensile strength (MPa),*
P_{max} = *Maximum load (N),*

A_o = *Original cross-sectional area* (mm^2).

12. Wear - The progressive damage, involving material loss, which occurs on the surface of a component as a result of its motion relative to the adjacent working parts; it is the almost inevitable companion of friction (Williams). Wear rate is calculated by Equation (4).

$$w = m / d \tag{4}$$

where

w = *Wear rate* (mg / m),
m = *Material loss* (mg),
d = *Sliding distance* (m).

1.4 Assumptions

This research assumed that the recycled HDPE, and recycled automotive tire rubber would combine uniformly during the extrusion process to form a composite material. It also assumed that the newly formed composite material can be injection molded to form test specimens.

1.5 Limitations

The findings of this study were limited by the following parameters.

1. The quality of the HDPE and the recycled automotive grade rubber is controlled by the suppliers.

2. Human error and the accuracy of the testing equipment may affect the accuracy of the test results.

3. Material characteristics may affect the processibility of the constituents being extruded and injection molded.

4. The mechanical properties, friction, and wear behavior of the composites are related to the capabilities of the extrusion and injection molding system used in this research.

1.6 Delimitations

The study was delimited by the following parameters.

1. The percentage of recycled automotive tire rubber mixed with recycled HDPE for this experiment was 0, 5, 10, 15, 20, 25, and 30 percent by weight.

2. Optimal processing parameters were employed for this experiment for both the extrusion and the injection molding processes.

3. The HDPE used in this research was supplied by Quantum Chemical Company, Heath, Ohio. The recycled automotive tire rubber used was supplied by Rubber Resource Technology, Macom, Missouri. The granular size of the rubber was screened to 40 mesh.

4. The composites were processed using a Killion KL - 125 extrusion compounding system with a Maddock mixer screw. The extruder has an L/D ratio of 30:1, and a die with a diameter of approximately 6.35 mm.

5. The composite test specimens were injection molded using a Boy 50M injection molding system. The injection molding system has an L/D ratio of 20.5:1, and ASTM test specimen molds.

1.7 Hypotheses

The composites will produce mechanical, friction, and wear properties different from those of recycled HDPE. The properties will vary with different recycled rubber percentages.

CHAPTER II

REVIEW OF RELATED RESEARCH

High Density Polyethylene (HDPE) is a product that has been on the world market for over forty years. It was first produced commercially in Germany, and is considered a great advancement over low density polyethylene because of its higher melting point and increased rigidity. Industry uses HDPE extensively for products such as juice, milk, and oil bottles, detergent containers, trash cans, flower pots, and traffic cones. Products made from HDPE are marked with a recycling symbol of number two in the center of a recycling triangle. This symbol was developed by the Society of Plastic Industry to aid in the separation of plastics for recycling.

Tires are made from synthetic vulcanized rubber. "A synthetic rubber may be defined as a substance that can be stretched to at least twice its original length and that after unloading returns to approximately its original length or position in a reasonable time" (Fisher, 1941). Synthetic rubber is used extensively in industry for tires, shoe soles, asphalt, automotive, and construction. Rubber recycling lags far behind that of HDPE, even though rubber articles have been recycled since 1853. Tires consume 51 percent of the rubber used in today's world, and the U.S. currently stockpiles over three billion used tires.

Rader, Baldwin, Cornell, Sadler, and Stockel (1995) state that as the 21st century nears, a perceived problem facing industrialized societies is the disposal of its solid waste. The majority of solid waste is disposed in landfills, with a small amount being incinerated or recycled. The solution to the waste disposal problem is ultimately dependent upon the recycling of polymers. In 1993, over 34 percent by weight of the total municipal solid waste stream was containers and packaging materials, of which plastics represent 12 percent or 7.2 billion kg. However, less than 500 million kg out of the worldwide production of 60 billion kg of plastics is recycled (Andrews &

Subramanian, 1992). The challenge is to process the trash into high valued materials that can be manufactured into products having acceptable value to a buyer.

McKirhan (1995) studied the mechanical properties and the processibility of composites of recycled HDPE, recycled rubber, ethyl co-vinyl acetate and poly (ε-caprolactone). Recycled HDPE was blended with recycled rubber and extruded at compositions ranging from zero to twenty-five percent. The results showed that the strength of composites of recycled HDPE and rubber particles decreased with increased rubber content. The ductility of recycled HDPE and rubber composites decreased drastically at rubber concentrations of five percent, then remained fairly constant as the rubber content increased. The hardness of recycled HDPE and rubber composites decreased with increased rubber particle content. There is no significant effect of rubber particle size on the strength of the composites. Finer particle size seemed to improve the ductility, but decreased the hardness of the composites of recycled HDPE and five percent recycled rubber particles. Akhtar *et al.* (1989) studied blends of 30, 50, and 70 percent natural rubber (polyisoprene) with polyethylene. The properties of these blends can be changed over a wide range and were comparable to those of thermoplastic elastomers. These blends could therefore be used as automobile filler panels, gaskets, seals, truck floor beds, cable insulation, and lawnmower wheels (Ulrich, 1993).

Williams (1994) defines tribology as the science and technology of interacting surfaces in relative motion, dealing with every aspect of friction, lubrication, and wear. In the United States, $200 billion was dissipated in 1985 due to friction and wear, accounting for three-quarters of the total loss (Rabinowicz, 1995). Plastics are particularly important to tribology. Booser (1994) attributed the following properties of plastics to their tribological applications: low inherent friction, low unlubricated wear rates, excellent fatigue resistance, absorption of shock and vibration, low maintenance, low weight, and low cost per unit volume. Under similar conditions, most plastics have lower friction than metals or other structural materials. They also resist galling and scuffing. These properties allow them to be used without additional lubrication for many applications.

Michael, Rabinowicz, and Iwasa (1991) studied the friction and wear of polymeric materials at various temperatures. The experiments determined the friction and wear coefficients of various polymer pins slid against either AISI 304 stainless steel or oxygen-free high conductivity copper at 293, 77 and 4.2 K. Three kinds of polymeric materials were tested, including unfilled, solid-lubricant filled and particle-reinforced plastics. Polymer friction is attributed to two principal causes. One is adhesion, the intermolecular bonding that occurs in the junctions which constitute the real area of contact between sliding materials. A second contribution to the friction coefficient is observed when the asperities, or high spots, on one surface penetrate into the opposing surface to an appreciable depth. The results of this study showed that the non-dimensional wear coefficients of polymers did not change as the temperature was changed, despite their increased hardness at lower temperatures. Moreover, it was concluded that adhesive wear was the dominant wear mechanism for polymers, at both room and cryogenic temperatures.

Spalding, Kirkpatrick, and Hyun (1993) investigated the coefficients of dynamic friction for low density polyethylene containing no additives. The polymer had a melt flow index of 2, and a solid density of 0.922 g/cm^3. The coefficients of dynamic friction were measured as a function of temperature at pressure levels of 0.69, 3.45, and 6.9 MPa and at roll velocity of 7.6, 15.2, and 30.5 cm s^{-1}. The results showed that the coefficient of friction decreased almost linearly as a function of temperature for each level of pressure, and the coefficient decreased as the pressure increased. Moreover, the coefficient of friction increased with roll speed for temperatures greater than 55°C.

Wolverton (1991) studied the friction and wear in plastic components. He stated that thermoplastic composites wear out at a rate determined by wear factor, coefficients of friction, and pressure-velocity limits. Wolverton also agreed that adhesion was the primary mechanism of polymer wear. His study showed that a polymer powder built up on mating surfaces was a sign of proper wear, as opposed to melted polymer, gouges and groves. Plastic to metal friction is characterized by adhesion and deformation with coefficient of friction being inversely proportional to load and proportional to speed. The smoothest range of metal finish (Ra surface finish .20 to .30 μm) caused the greatest wear on composites. In contrast, the surface finish of .30 to .40 μm offered the lowest wear factor, while surface finish of 1.20 to 1.70 μm generally caused moderate wear on composites. In plastic-on-plastic wear applications, composite pairs having similar wear factors are preferred to pairs having large differences in wear factor, provided that total wear is acceptably low.

CHAPTER III

METHODOLOGY

3.1 Materials

For this research, virgin high density polyethylene (HDPE) was supplied by Quantum Chemical Company in pellet form. Approximately 45.36 kg of virgin HDPE was extruded to create recycled HDPE. The parameters for extruding virgin HDPE are shown in Table 1. The recycled rubber particles were supplied by Rubber Resource Technology, Macom, Mossouri. The particle size of recycled rubber used in this research was 40 mesh (0.420 mm - 0.297 mm).

The recycled rubber and recycled HDPE were weighed separately, and thoroughly mixed to create 4.5 kg batches. The content of recycled rubber introduced into the recycled HDPE was 0, 5, 10, 15, 20, 25, and 30 percent by weight.

3.2 Processing

The batches were fed individually into a Ktron 2 volumetric feeder. The feeder mixed the material and forced the mixture into the extruder. The feeder speed is shown in Table 1. Each batch was pre-heated in the extruder hopper for 15 minutes before extrusion.

Once the barrel temperatures on Killion KL - 125 extruder were reached and stabilized for at least 30 minutes as in Table 1, the screw drive was turned on, and set to the optimal screw speed. The setting of the screw was set to appropriately mix the materials. The extrudate was forced out of the die, cooled by ambient air, and further cooled by a water trough. The water was circulated with a water pump in a water trough of three meters long.

Upon exiting the water trough, the extrudate passed through a Huestis air dryer. The dryer blew air onto the extrudate as it was pulled into a Killion pelletizer. The speed of the pelletizer to pull the extrudate was adjusted to match the speed for the extrudate exiting the die on the extruder. The pelletizer cut the extrudate into pellets, and dispensed them into a bucket.

Table 1. Extrusion parameters for virgin and recycled HDPE, and composites of recycled HDPE and recycled rubber particles

Operation Variables	Virgin HDPE & Recycled HDPE	Recycled HDPE w/ 5% Rubber	Recycled HDPE w/ 10% Rubber	Recycled HDPE w/ 15% Rubber	Recycled HDPE w/ 20% Rubber	Recycled HDPE w/ 25% Rubber	Recycled HDPE w/ 30% Rubber
Feeder Speed	150 rpm	150 rpm	150 rpm	150 rpm	150 rpm	150 rpm	150 rpm
Barel Temperature: Zone 1	176.5°C (350°F)	176.5°C (350°F)	176.5°C (350°F)	176.5°C (350°F)	176.5°C (350°F)	176.5°C (350°F)	176.5°C (350°F)
Zone 2	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)
Zone 3	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)	190.3°C (375°F)
Zone 4	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	195.9°C (385°F)
Clamp Ring	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	195.9°C (385°F)
Die	209.7°C (410°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)	204.2°C (400°F)
Melt Temperature	212.5°C (415°F)	212.5°C (415°F)	212.5°C (415°F)	212.5°C (415°F)	212.5°C (415°F)	212.5°C (415°F)	204.2°C (400°F)
Barrel Pressure	5.49 MPa	5.49 MPa	2.76MPa	2.76 MPa	2.53 MPa	2.46 MPa	2.46 MPa
Tachometer	5.0 rpm	5.0 rpm	3.0 rpm	3.0 rpm	2.5 rpm	2.0 rpm	2.0 rpm
Room Temperature	26.6°C (80°F)	23.8°C (75°F)	23.8°C (75°F)	23.8°C (75°F)	23.8°C (75°F)	22.7°C (73°F)	22.7°C (73°F)
Cooling Water Temperature	25.5°C (78°F)	25.5°C (78°F)	21.6°C (71°F)	21.6°C (71°F)	21.6°C (71°F)	21.0°C (70°F)	21.0°C (70°F)

Each batch of pelletized material was dried and dehumidified for 1 hour at 92.3°C (200°F). The batch was then fed into the hopper of a Boy 50M injection molding machine. The injection molder was set up according to the parameters shown in Table 2. Once the barrel temperatures were reached, the molder was put into automatic production mode. The machine screw forced the polymeric melt into the mold, which formed ASTM test specimens. Once cooled, the mold opened and released the formed specimens. The process automatically repeated to continually produce specimens.

Table 2. Injection molding parameters for recycled HDPE, and composites of recycled HDPE with 5, 10, 15, 20, 25, 30 percent recycled rubber

Zone	Nozzle	Zone 4	Zone 2	Zone 1	Molds	
Temperature	215.3°C (420°F)	215.3°C (420°F)	198.7°C (390°F)	176.5°C (350°F)	21.0°C (70°F)	
Plasticating	0	1	2	Plate End		
Position	0.0 cm	2.0 cm	33.0 cm	50.0 cm		
Screw Feed	25%	25%	25%	25%		
Back Pressure	100 psi	100 psi	100 psi	100 psi		
Injection (Filling)	6	5	4	3	2	1
Position	3.0 cm	18.1 cm	27.5 cm	33.9 cm	41.2 cm	50.0 cm
Injection Feed	20%	20%	30%	30%	20%	20%
Injection Pressure	900 psi	900 psi	900 psi	900 psi	900 psi	900 psi
Injection (Hold)	0	5	10	15		
Hold Pressure	600 psi	600 psi	700 psi	800 psi		

3.3 Mechanical Property Testing

Tensile strength and percent elongation were tested on the molded ASTM dog-bone specimens. Five specimens were chosen randomly from every batch and tested for ultimate tensile strength and percent elongation on an Instron 4467 universal testing system. The testing speed was 30 mm min^{-1}.

Durometer hardness was tested on the ASTM dog-bone specimens. Each specimen was tested in five randomly chosen locations using an automated type “D” Durometer controlled by a microcomputer. The Durometer hardness reading was taken after 1 second of penetration onto the specimens.

Impact strength was tested using Izod impact specimens and a BLI impact tester. The specimens were machined to ASTM specifications (ASTM D256). Three impact tests were performed for each batch using the 2 ft-lb. scale.

3.4 Friction and Wear Tests

Friction and wear tests were performed using a pin-on-disk wear tester. The disk was made of AISI 52100 high carbon steel and had a diameter of 10.16 cm. The disc surface was machined and buffed to a roughness of 0.48μm. Before testing, the disk surface was cleaned with methyl alcohol, and the specimen was ultrasonically cleaned. Each specimen was installed on the wear tester and balanced before any load was applied. Wear was measured by weighing the specimen at time intervals of 0, 5, 10, 20, 30, 40, 50, and 60 min. By recording the weight loss, wear rate for each specimen was determined. Friction force was measured by a transducer, and recorded by a data acquisition system. LabView, the computer program, took ten readings every second and averaged them.

Three friction and wear experiments were performed on the composites of recycled HDPE and recycled rubber. The first experiment studied the effect of sliding speed on coefficient of friction and wear rate. Specimens containing five percent rubber, were tested under a normal pressure of 16.46 MPa. Sliding speeds of 2.55, 3.40, 4.25, 5.10, and 5.95 m s^{-1} were used. Three specimens were tested for each test condition and the results were averaged.

The second experiment determined the effect of normal pressure on coefficient of friction and wear rate. Specimens containing five percent recycled rubber were tested at a sliding speed of 5.10 m s^{-1}. Normal pressures of 9.87, 13.16, 16.46, 19.75, and 24.60 MPa were investigated. Three specimens were tested for each load and the results were averaged.

The third experiment determined the effect of recycled rubber percentage on coefficient of friction and wear rate. A normal pressure of 16.46 MPa and a sliding speed of 5.10 m s^{-1} were used. Rubber percentages of 0, 5, 10, 15, 20, 25, and 30 percent by weight were tested. Each composite with different rubber percentage was tested three times and the results were averaged.

3.5 Microscopic Analysis

After the friction and wear experiments were performed, a microscopic analysis of the test specimen structure was performed. This observation was needed to understand how the material properties were changed due to sliding. All specimens were observed using a Buehler Versamet 3 microscope at a magnification of 243.3 X. Images were recorded using a Sony CCD-IRIS/RGB color video camera, which were captured by a microcomputer running Image Pro Plus software.

The fist series of microscopic analysis were made on wear test surfaces of specimens. No specimen preparation was required for these observations. These observations provided evidence of the surface damage occurred due to dry sliding.

The second series of microscopic analysis showed structural change within the test specimen. This was achieved by observing the cross section of the specimen. Specimens were prepared by casting them in Buehler Ultra Mount compound. Once the compound was hardened, the mounted specimen was cross sectioned by using a Buehler Surfmet II belt sander. One third of the original specimens thickness was removed. To remove the sanding marks, the specimen was first sanded with Buehler Handimet with pressure sensitive abrasive papers, and then polished on a polishing wheel. Aqueous solution of alumina (0.05 μm, Buehler Micropolish) was applied on the wheel to aid the polishing process.

CHAPTER IV

PRESENTATION AND INTERPRETATION OF DATA

4.1 Analysis of Variance

Analysis of variance (ANOVA) was performed on all test results, including tensile strength, percent elongation, hardness, impact strength, coefficient of friction and wear rate. Statistical analysis system (SAS) under Unix operating system was used to perform ANOVA with general linear model (GLM) procedure for all test results. The GLM procedure determined the significance of the results. Table 3 displays the ANOVA results.

Table 3. ANOVA Table

Test Number	Independent Variable	Dependent Variable	Significance
1	Rubber Concentration (%)	Tensile Strength (MPa)	Yes, PR>F=0.0001 (99.99%)
2	Rubber Concentration (%)	Percent Elongation (%)	Yes, PR>F=0.0001 (99.99%)
3	Rubber Concentration (%)	Hardness After 1.0 Second	Yes, PR>F=0.0001 (99.99%)
4	Rubber Concentration (%)	Impact Resistance (J-m^2)	Yes, PR>F=0.0001 (99.99%)
5	Sliding Speed (m s^{-1})	Wear Rate (mg m^{-1})	Yes, PR>F=0.0283 (97.17%)
6	Sliding Speed (m s^{-1})	Coefficient of Friction (μ)	Yes, PR>F=0.0285 (97.15%)
7	Normal Pressure (MPa)	Wear Rate (mg m^{-1})	Yes, PR>F=0.0001 (99.99%)
8	Normal Pressure (MPa)	Coefficient of Friction (μ)	Yes, PR>F=0.0001 (99.99%)
9	Rubber Concentration (%)	Wear Rate (mg m^{-1})	Yes, PR>F=0.0001 (99.99%)
10	Rubber Concentration (%)	Coefficient of Friction (μ)	Yes, PR>F=0.0001 (99.99%)

4.2 Effects of Recycled Rubber Percentage on Mechanical Properties

Figure 1 shows the effect of recycled rubber percentage on tensile strength of composites of recycled HDPE and recycled rubber. There is a negative correlation between recycled rubber percentage and tensile strength. As the recycled rubber content increased, the tensile strength of the composite material decreased. The confidence level for the data in Figure 1 was 99.99 percent.

Figure 2 shows the effect of recycled rubber percentage on percent elongation of composites of recycled HDPE with recycled rubber. There is a drastic decrease in percent elongation as the rubber percentage increased to five percent. Recycled HDPE (0 percent recycled rubber) had an elongation of 375 percent. With five percent recycled rubber, the elongation dropped to 67 percent. From five to 30 percent recycled rubber, the percent elongation decreased gradually. The confidence level of the data in Figure 2 was 99.99 percent.

Figure 3 displays the effect of recycled rubber percentage on Durometer hardness of composites of recycled HDPE with recycled rubber. The readings in this figure were taken after 1.0 second of penetration. The hardness of the material decreased as the recycled rubber content increased. A more drastic change occurs from 0 to 10 percent recycled rubber, than from 10 to 30 percent recycled rubber. The confidence level of the data in Figure 3 was 99.99 percent.

Figure 4 shows the effect of recycled rubber percentage on impact resistance of composites of recycled HDPE with recycled rubber. There was a major decrease in impact resistance as the rubber percentage increased to five percent. The impact strength of composites remained fairly constant between five and 25 percent of recycled rubber. A

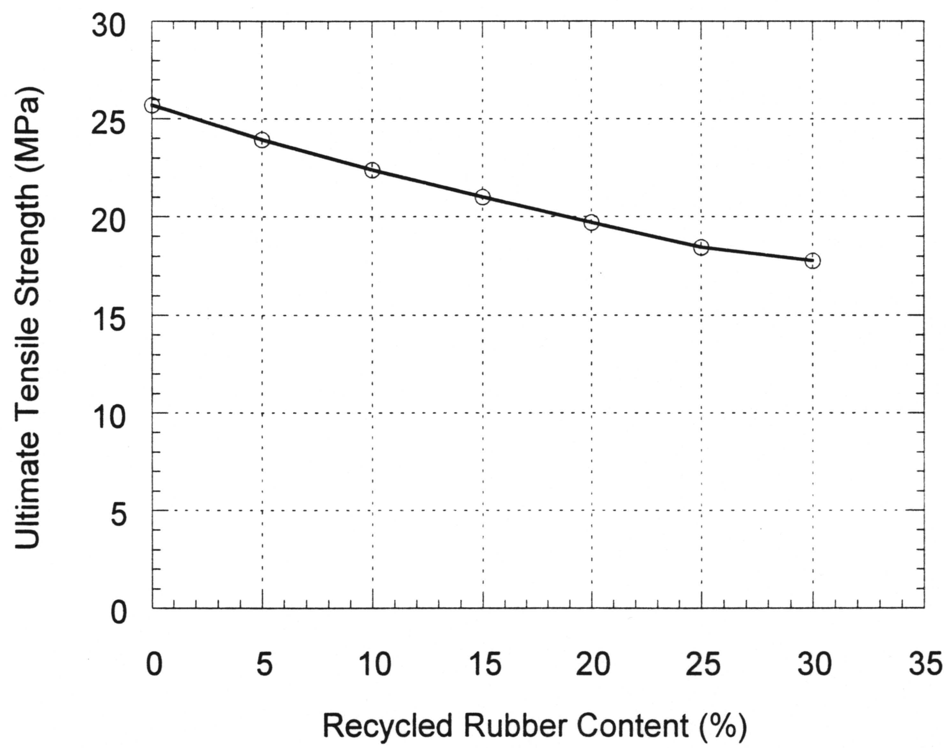

Fig. 1 Variation of ultimate tensile strength with recycled rubber content for composites of recycled HDPE with recycled rubber

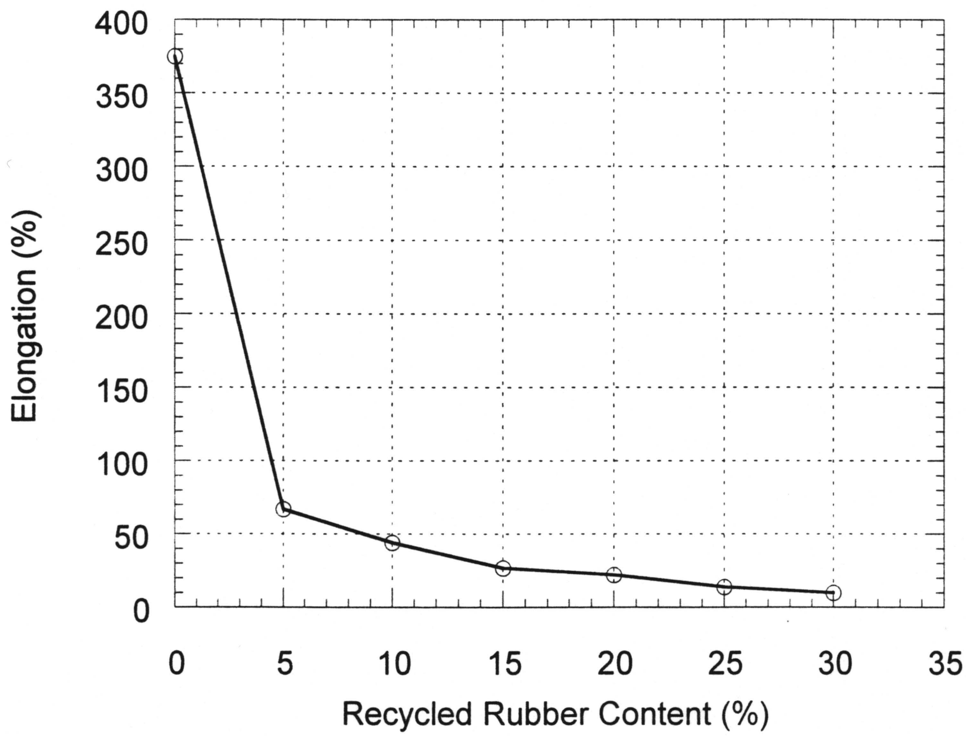

Fig. 2 Percent elongation as a function of recycled rubber content for composites of recycled HDPE with recycled rubber

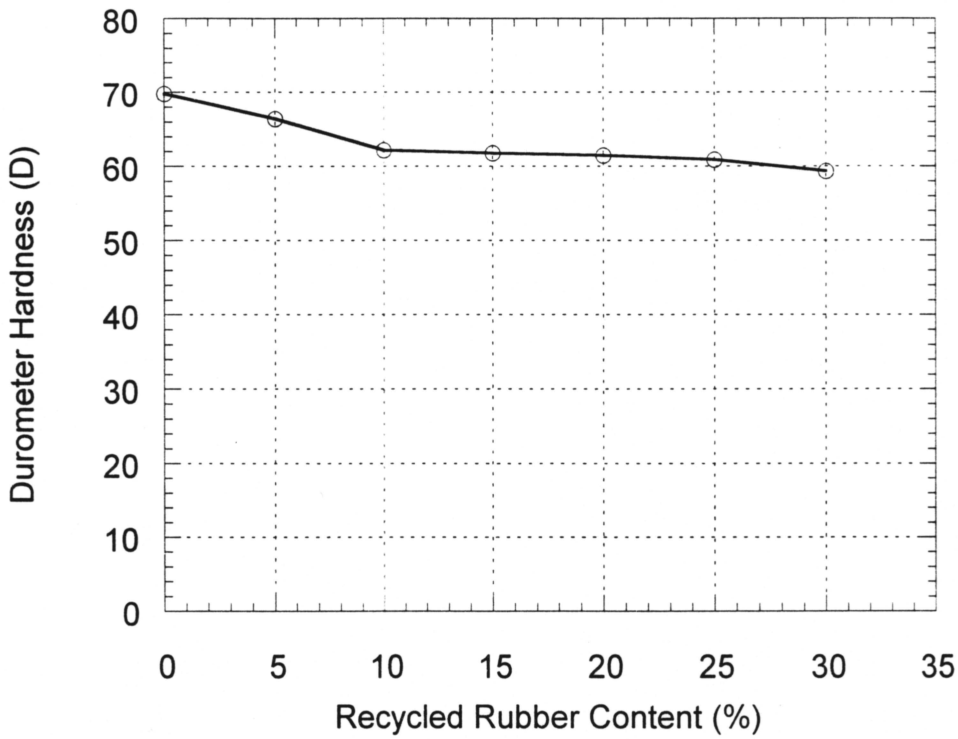

Fig. 3 Variation of Durometer hardness with recycled rubber content for composites of recycled HDPE with recycled rubber

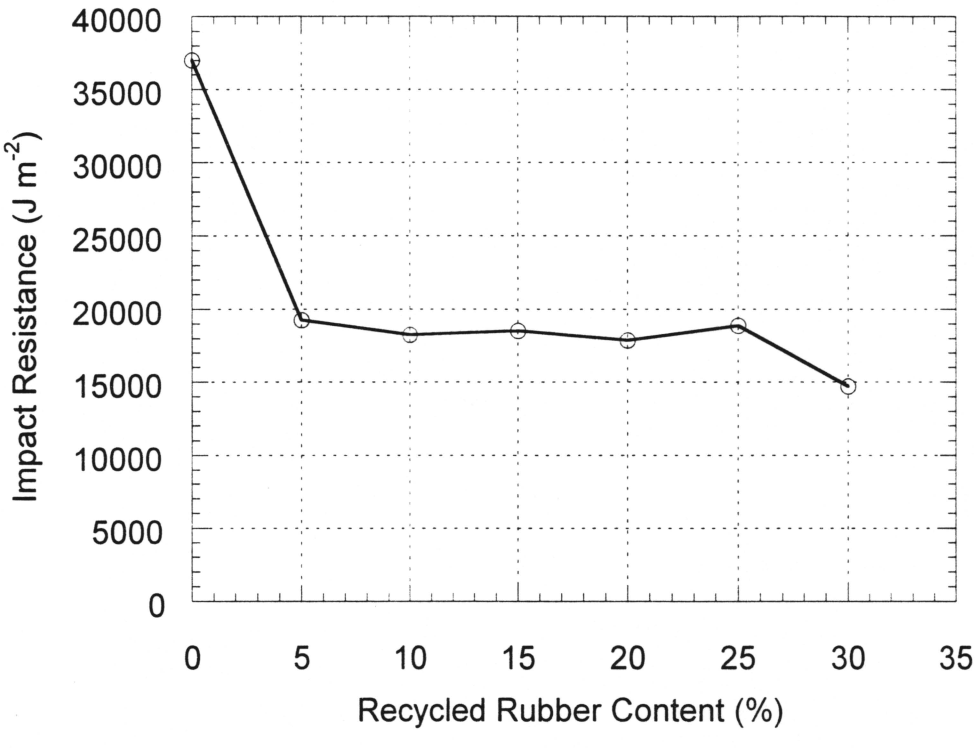

Fig. 4 Variation of impact resistance with recycled rubber content for composites of recycled HDPE with recycled rubber

significant reduction in impact resistance was observed again at 30 percent of recycled rubber. The confidence level of the data in Figure 4 was 99.99 percent.

The results of this section showed that as recycled rubber content in the composites increased, the tensile strength, percent elongation, and durometer hardness decreased. The impact resistance also decreased as recycled rubber content increased from zero to five percent. From five to 25 percent recycled rubber content, the impact resistance remained fairly constant, and it decreased further as the recycled rubber increased to 30 percent.

4.3 Effect of Sliding Speed on Friction and Wear

Figure 5 shows the effect of sliding speed on coefficient of friction for composites of recycled HDPE with five percent recycled rubber. It is noted that coefficient of friction increased slightly with increasing sliding speed. The confidence level of the data in Figure 5 was 97.15 percent.

Figure 6 shows the effect of sliding speed on wear rate for composites of recycled HDPE with five percent recycled rubber. As sliding speed increased, wear rate increased. The increase in coefficient of friction from 2.55 to 5.10 m s^{-1} was fairly consistent, while the increase from 5.10 to 5.95 m s^{-1} was more drastic. The confidence level of the data in Figure 6 was 97.17 percent.

Figure 7a is a micrograph of the surface of recycled HDPE with five percent recycled rubber before friction and wear test. In this picture, the original specimen preparation marks can be seen. Figure 7b is microscopic photograph of the surface of recycled HDPE with five percent recycled rubber after 1 hour of sliding at a speed of 2.55

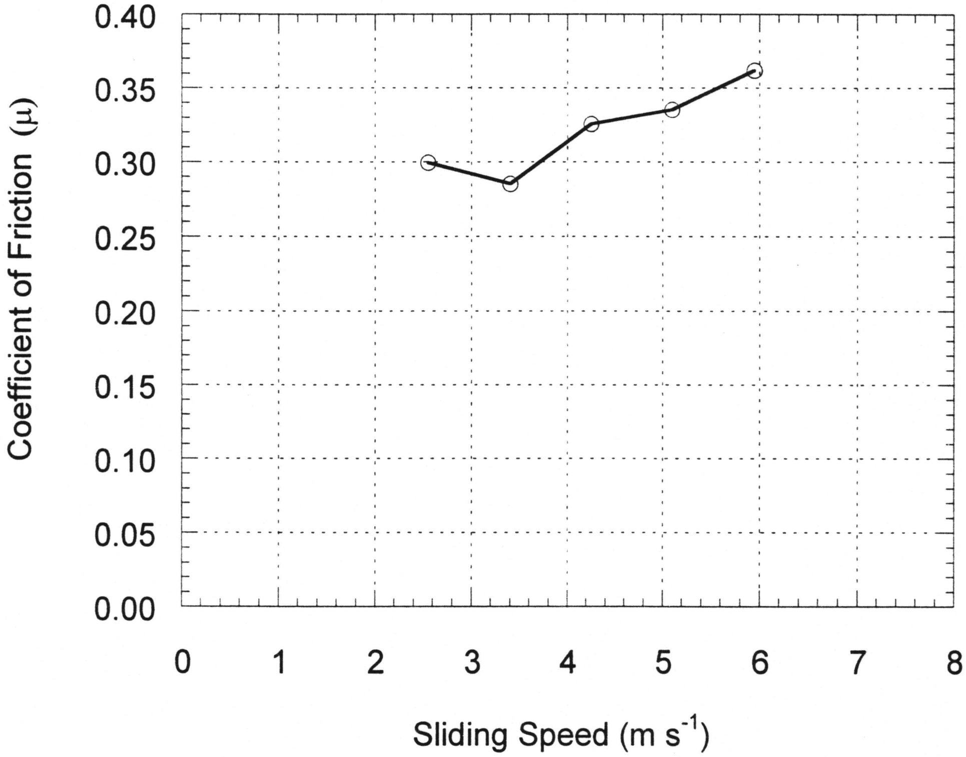

Fig. 5 Variation in coefficient of friction with sliding speed for composites of recycled HDPE with 5% recycled rubber

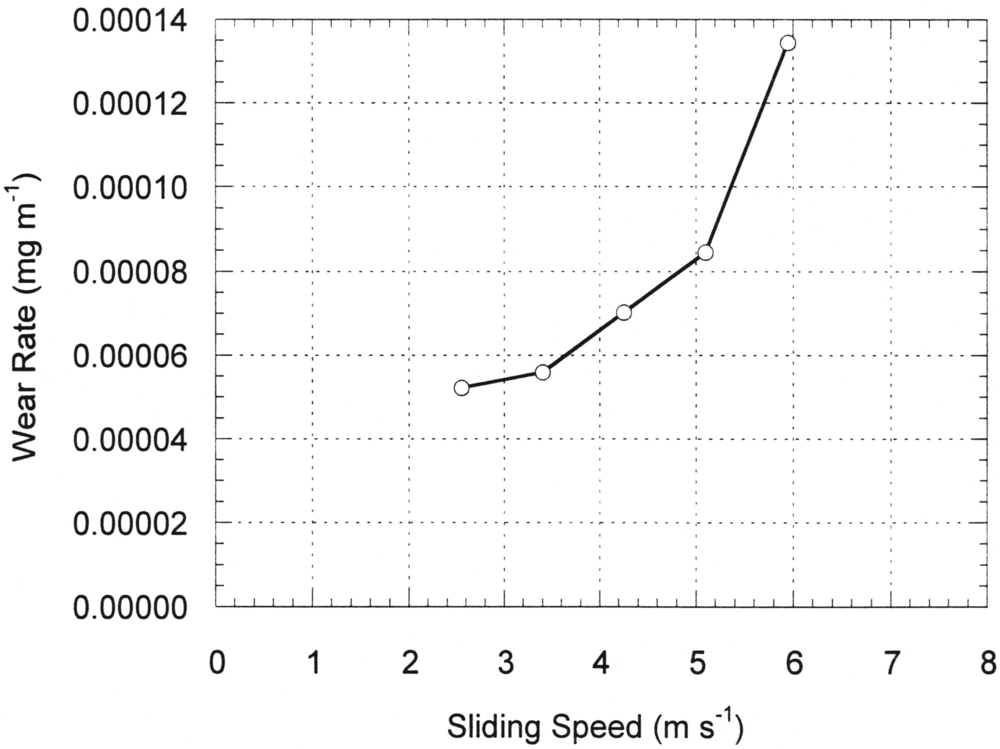

Fig. 6 Variation in wear rate with sliding speed for composites of recycled HDPE with 5% recycled rubber

Fig. 7 Surface micrographs of composites of recycled HDPE with 5% recycled rubber: (a) before sliding; (b) after 1 hour at 2.55 m s^{-1}; (c) after 1 hour at 5.95 m s^{-1} (243.3X)

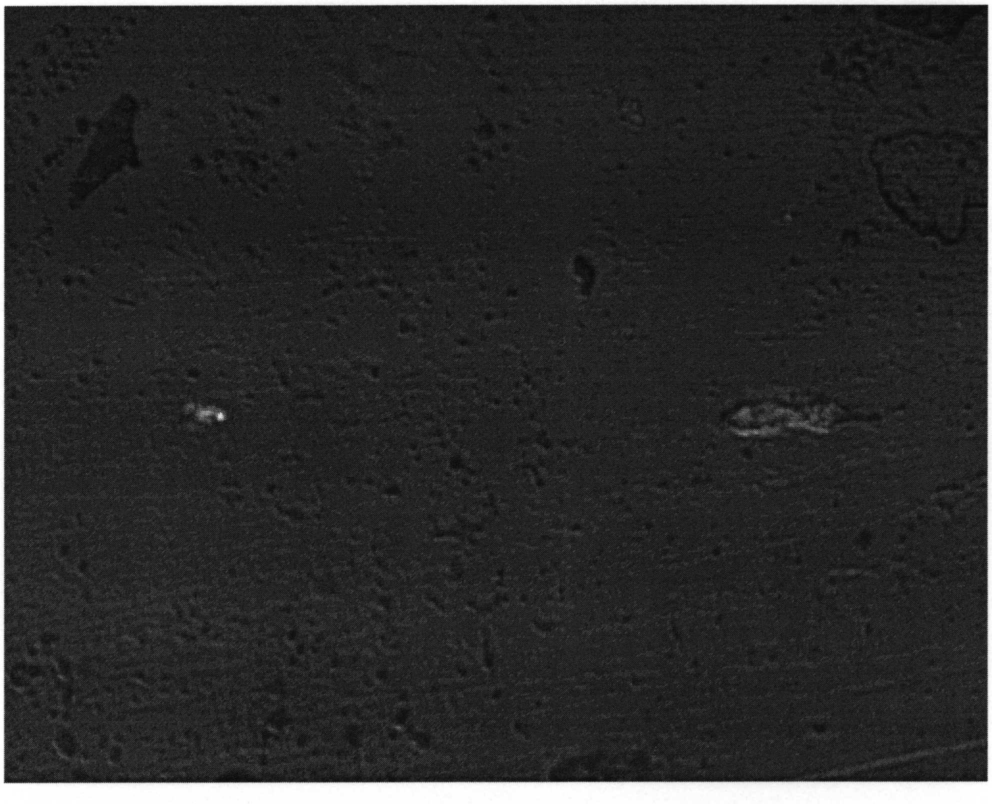

Fig. 7b

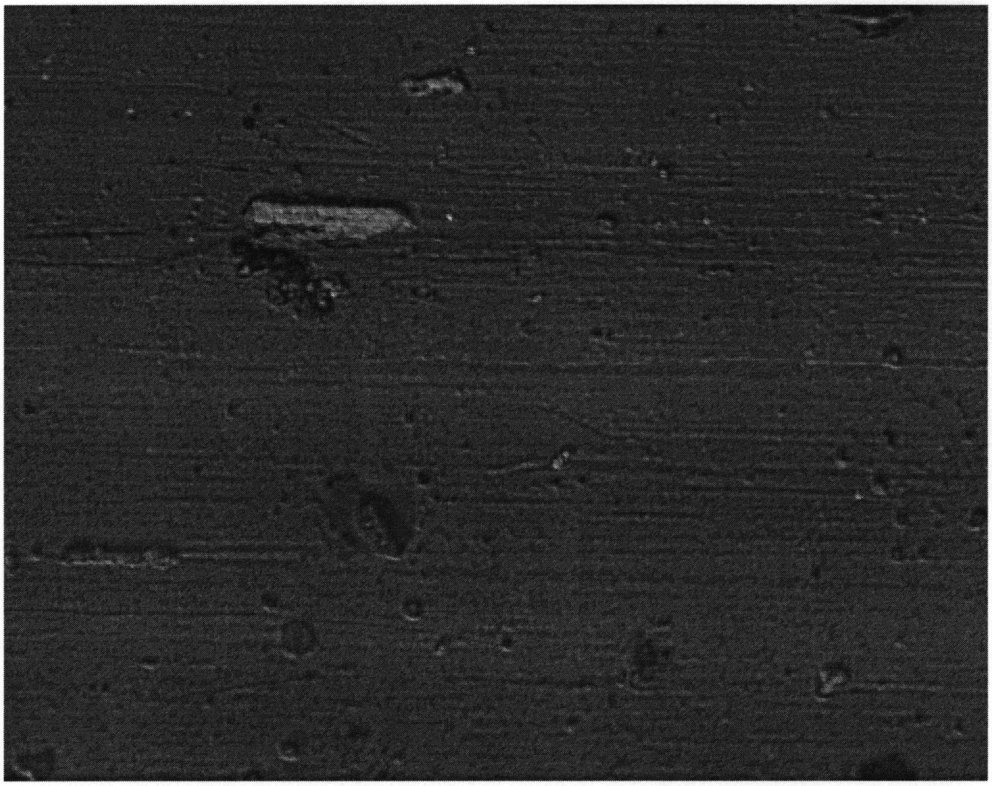

Fig. 7c

m s^{-1} and a normal pressure of 16.46 MPa. This photo shows that the sliding caused a polishing effect on the material.

Figure 7c is a micrograph of the surface of recycled HDPE with five percent recycled rubber after 1 hour of sliding at 5.95 m s^{-1} and a normal pressure of 16.46 MPa. The increased sliding speed caused less polishing effect, but more cutting on the material. This is shown by the horizontal plowing marks appeared in the picture.

Figure 8a is a micrograph of the cross section of recycled HDPE with five percent recycled rubber. This picture was taken on a specimen before any testing was performed. The diagonal grooves in the picture are from specimen preparation.

Figure 8b is a micrograph of the cross section of recycled HDPE with five percent recycled rubber tested for 1 hour at a sliding speed of 2.55 m s^{-1} and under a normal pressure of 16.46 MPa. In this picture the depth of deformation on the material due to sliding can be seen.

Figure 8c is a micrograph of the cross section of recycled HDPE with five percent recycled rubber tested for 1 hour at a sliding speed of 5.95 m s^{-1} and under a normal pressure of 16.46 MPa. This picture shows a decreased depth of deformation layer on the material compared with a lower sliding speed of 2.55 m s^{-1} on Figure 8b.

As can be seen from the results in this section, both coefficient of friction and wear rate increased with increased sliding speed. Increased sliding speed caused more severe damage on the specimen surface. However, increasing speed seemed to result in thinner subsurface deformation layer.

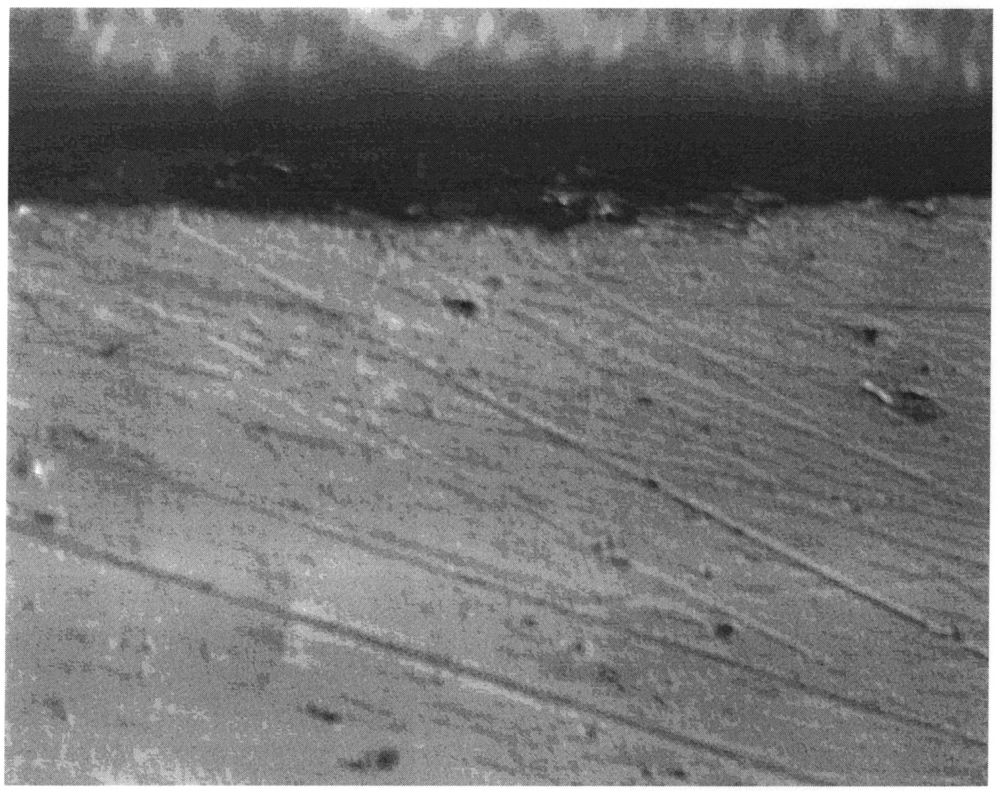

Fig. 8 Cross section of recycled HDPE with 5% recycled rubber: (a) before wear testing; (b) after 1 hour of sliding at 2.55 m s^{-1}; (c) after 1 hour of sliding at 5.95 m s^{-1} (243.3 X)

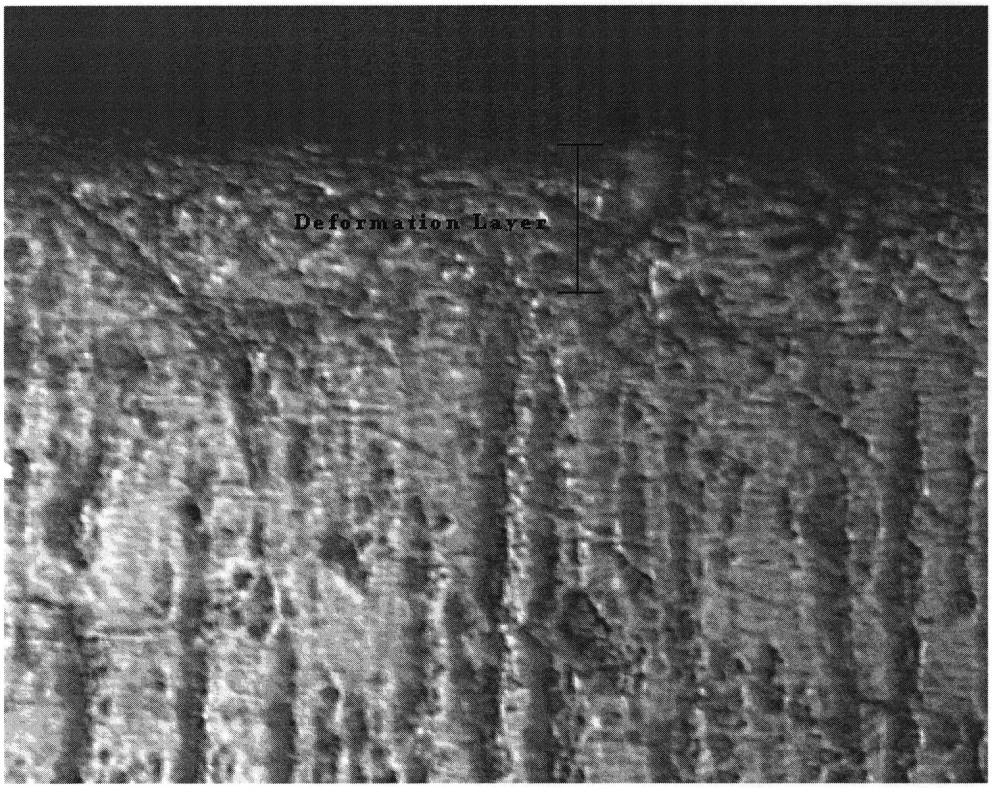

Fig. 8b

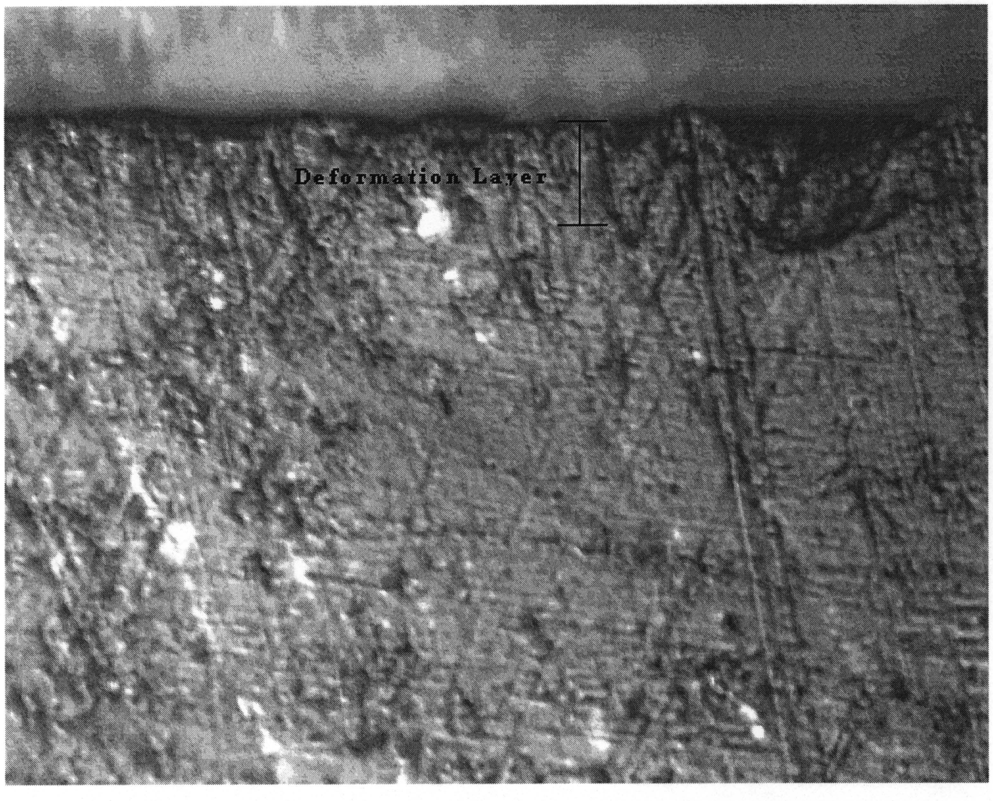

Fig. 8c

4.4 Effect of Normal Pressure on Friction and Wear

Figure 9 shows the effect of normal pressure on coefficient of friction for a composite of recycled HDPE with five percent recycled rubber. This figure shows that as normal pressure increased, coefficient of friction also increased. The confidence level of the data in Figure 9 was 99.99 percent.

Figure 10 shows the effect of normal pressure on wear rate of recycled HDPE with five percent recycled rubber. As normal pressure increased, wear rate increased. The increase in wear rate with normal pressure is almost linear. The confidence level of the data in Figure 10 was 99.99 percent.

Figure 11a is a micrograph of the surface of recycled HDPE with five percent recycled rubber after 1 hour of sliding under a normal pressure of 9.87 MPa. The sliding speed was 5.10 m s^{-1}. Compared with the original surface shown in Figure 7a, this picture shows that the applied load still caused a limited polishing effect on the material. A smooth film over the surface was created due to sliding.

Figure 11b shows a micrograph of the surface of recycled HDPE with five percent recycled rubber after 1 hour of sliding under a normal pressure of 24.60 MPa. The sliding speed was 5.10 m s^{-1}. The increased load has caused severe deformation perpendicular to the wear track on the surface. The severe deformation is partially due to vibration of the specimen during testing.

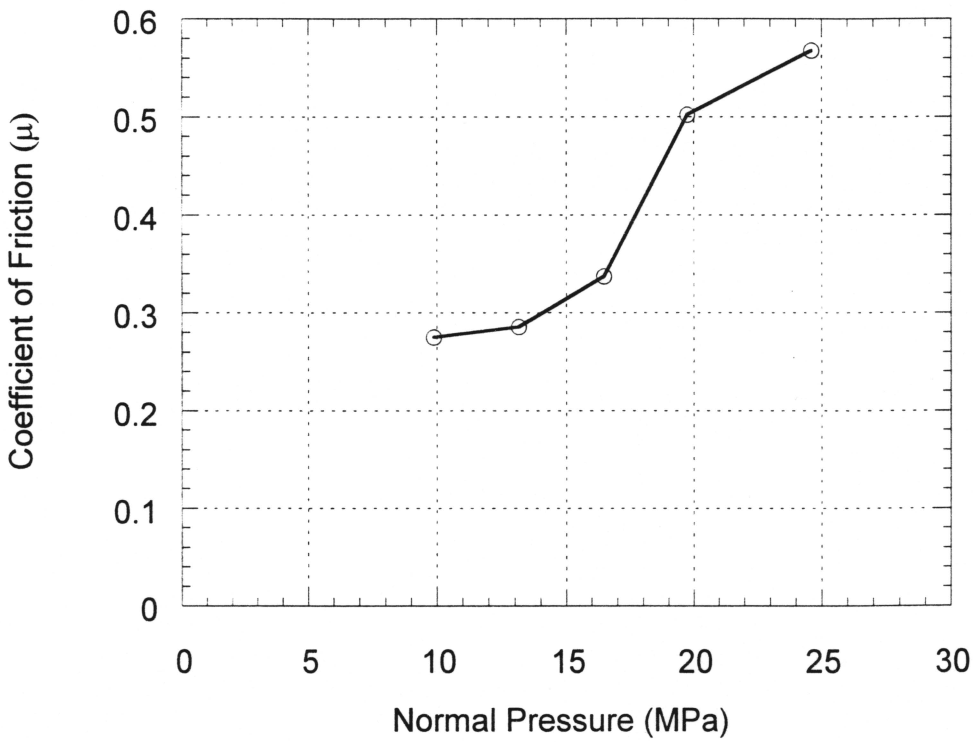

Fig. 9 Coefficient of friction as a function of normal pressure for a composite of recycled HDPE with 5% recycled rubber

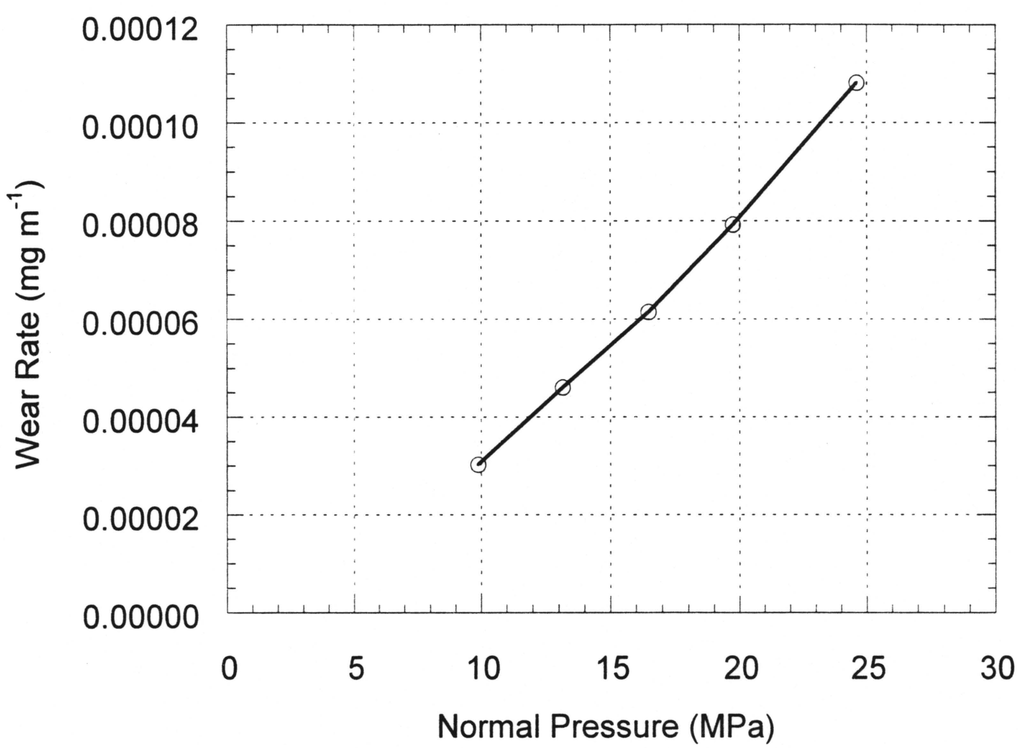

Fig.10 Wear rate as a function of normal pressure for a composite of recycled HDPE with 5% recycled rubber

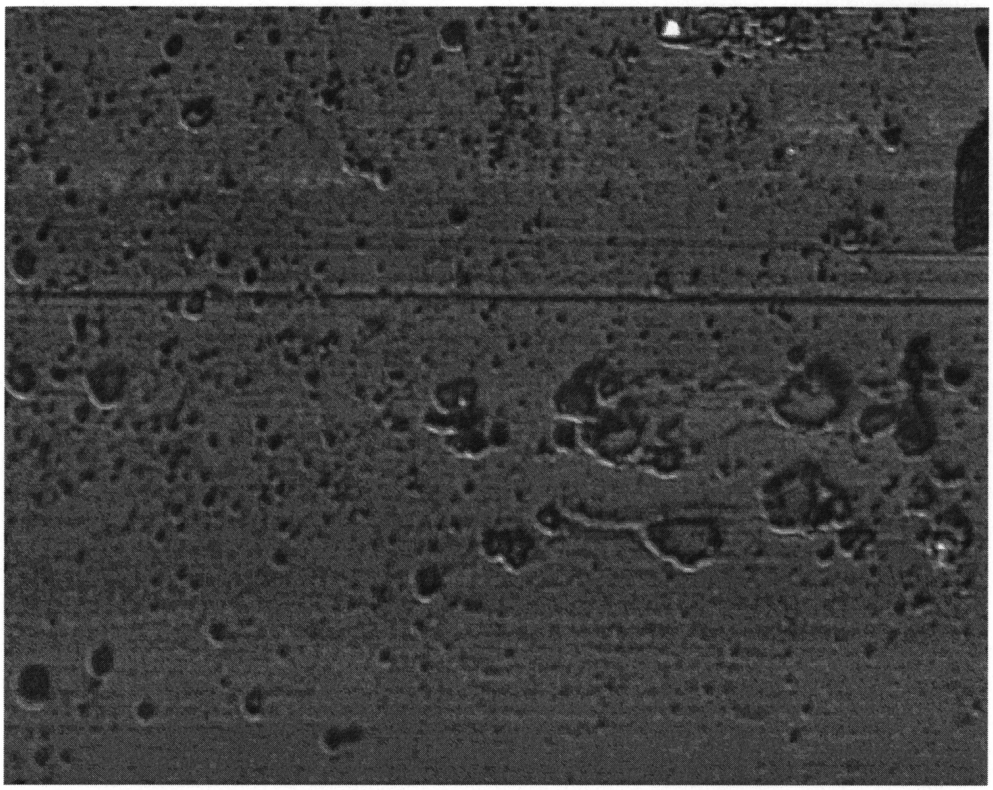

Fig.11 Surface micrographs of recycled HDPE with 5% recycled rubber: (a) after 1 hour of sliding under 9.87 MPa; (b) after 1 hour of sliding under 24.60 MPa. The sliding speed was 5.10 m s^{-1} (243.3 X)

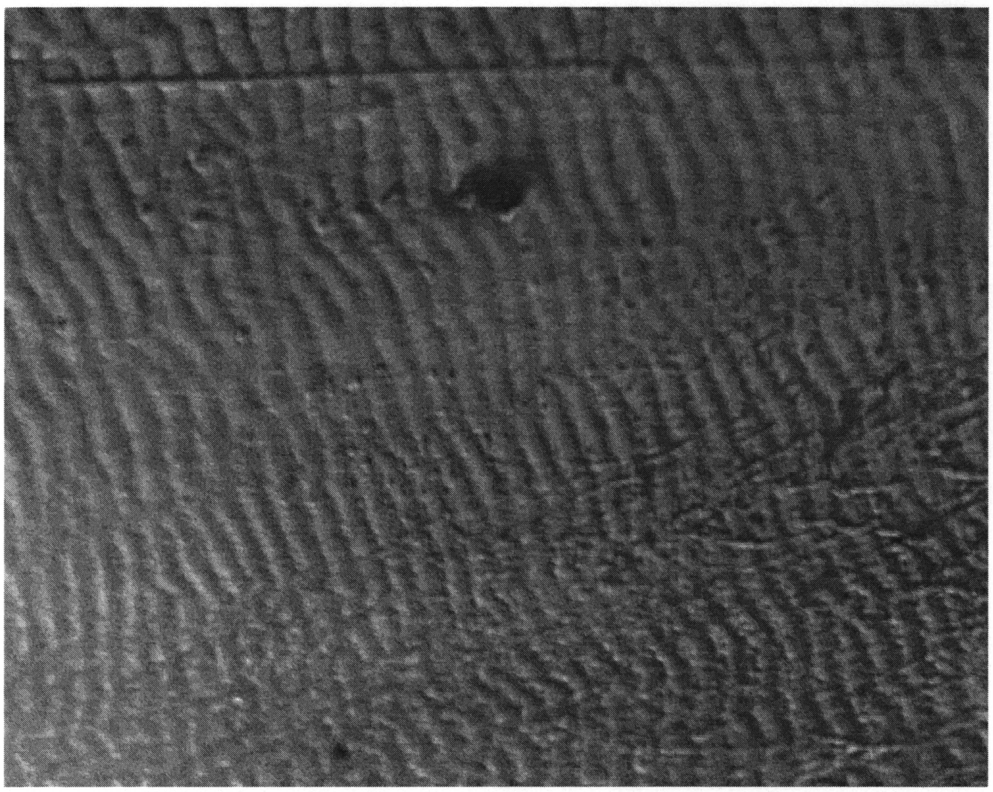

Fig.11b

Figure 12a is a micrograph of the cross section of recycled HDPE with five percent recycled rubber. This specimen was tested for 1 hour with a normal pressure of 9.87 MPa and a sliding speed of 5.10 m s^{-1}. In this picture the depth of deformation on the material due to the sliding process can be seen.

Figure 12b is a microscopic photograph of the cross section of recycled HDPE with five percent recycled rubber. This specimen was tested for 1 hour under a normal pressure 19.75 MPa. This picture shows more severe damage on subsurface region of the composite due to increased normal pressure.

The results in this section show that both coefficient of friction and wear rate increased with increased normal pressure. Increased normal pressure caused more severe damage on the surface. Moreover, increased normal pressure resulted in a thicker subsurface deformation layer.

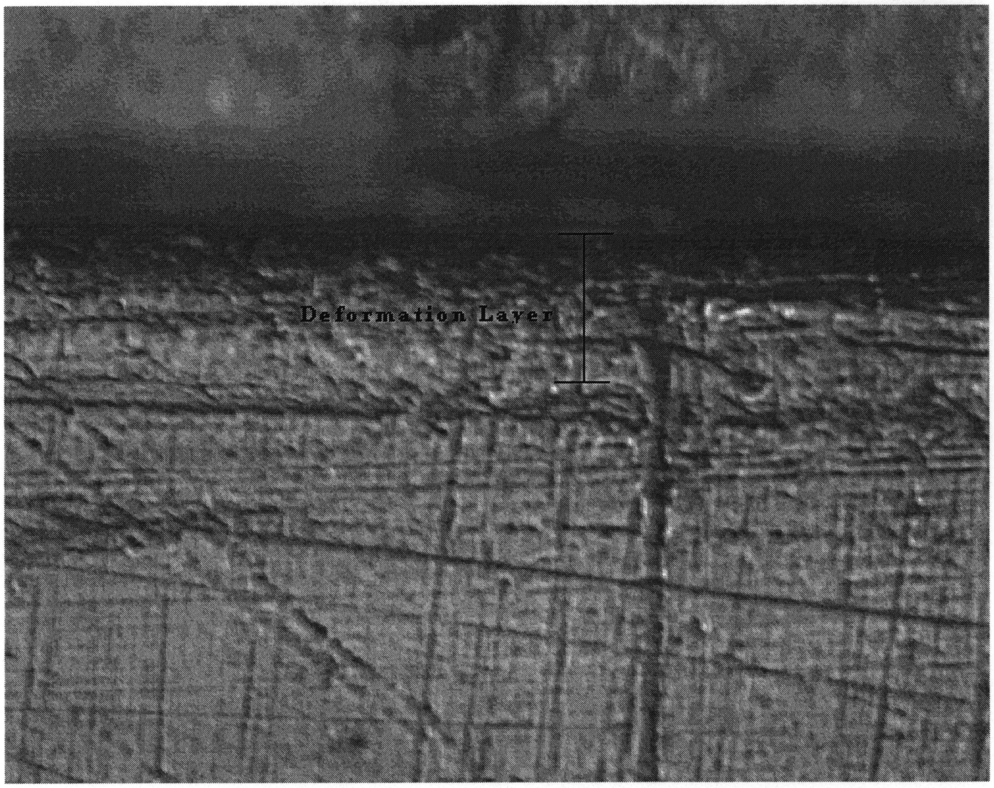

Fig.12 Cross section of recycled HDPE with 5% recycled rubber: (a) after 1 hour of sliding under a normal pressure of 9.87 MPa; (b) after 1 hour of sliding under a normal pressure of 19.75 MPa (243.3 X)

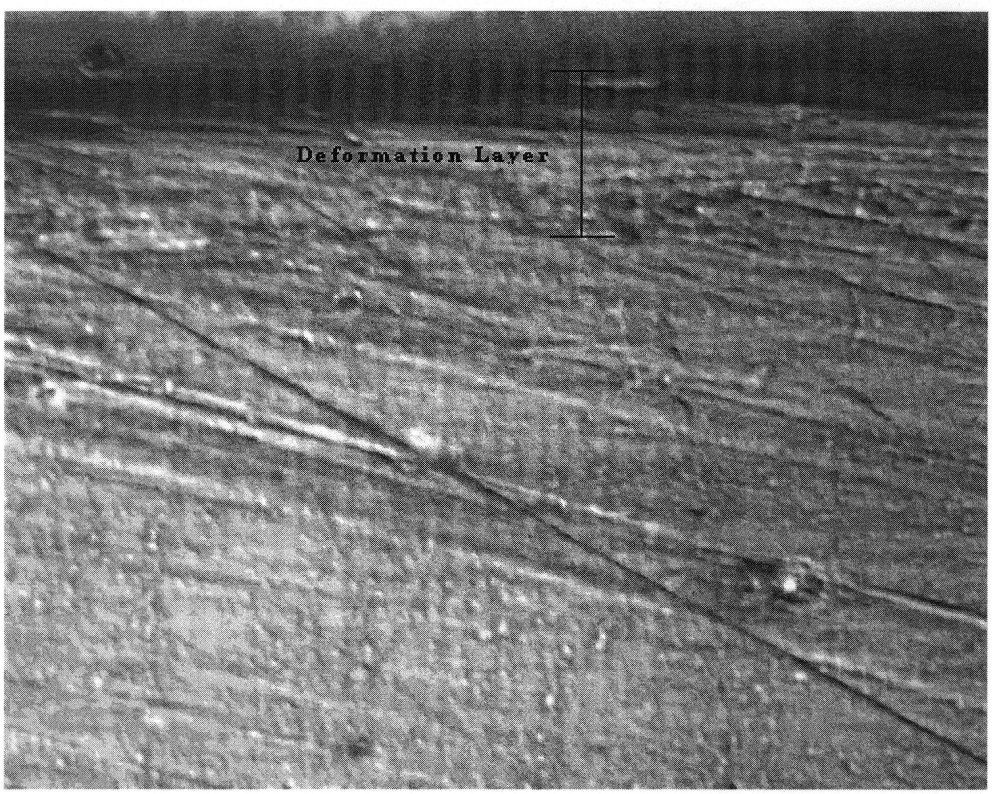

Fig.12b

4.5 Effects of Recycled Rubber Content on Friction and Wear

Figure 13 shows the effect of recycled rubber content on coefficient of friction for composites of recycled HDPE with recycled rubber. The sliding condition included a normal pressure of 16.46 MPa and a sliding speed of 5.10 m s^{-1}. As recycled rubber content increased, coefficient of friction increased. Prior to a rubber content of 20 percent, this increase was fairly consistent, where the coefficient of friction rose from 0.337 to 0.507 when rubber content increased from five to 20 percent. The increase in coefficient of friction became less drastic after 20 percent rubber content. The confidence level of the data in Figure 13 was 99.99 percent.

Figure 14 shows the effect of recycled rubber content on wear rate for composites of recycled HDPE with recycled rubber. The sliding condition included a normal pressure of 16.46 MPa and a sliding speed of 5.10 m s^{-1}. As recycled rubber content increased, wear rate increased. The biggest increase occurred from 0 to five percent rubber content. The confidence level of the data in Figure 14 was 99.99 percent.

Figure 15a is a micrograph of the surface of recycled HDPE with 10 percent recycled rubber. This photograph was taken after 1 hour of testing with a sliding speed of 5.10 m s^{-1} and a normal pressure of 16.46 MPa. In this picture, some of the original specimen preparation marks can still be seen. There are also small voids present where the rubber particles were once bonded with the HDPE.

Figure 15b shows the surface micrograph of recycled HDPE with 20 percent recycled rubber. This picture was taken after 1 hour of testing with a sliding speed of 5.10 m s^{-1} and a normal pressure of 16.46 MPa. In this picture, plowing marks due to the sliding can be seen. Moreover, there are large gouges on the surface due to the increased

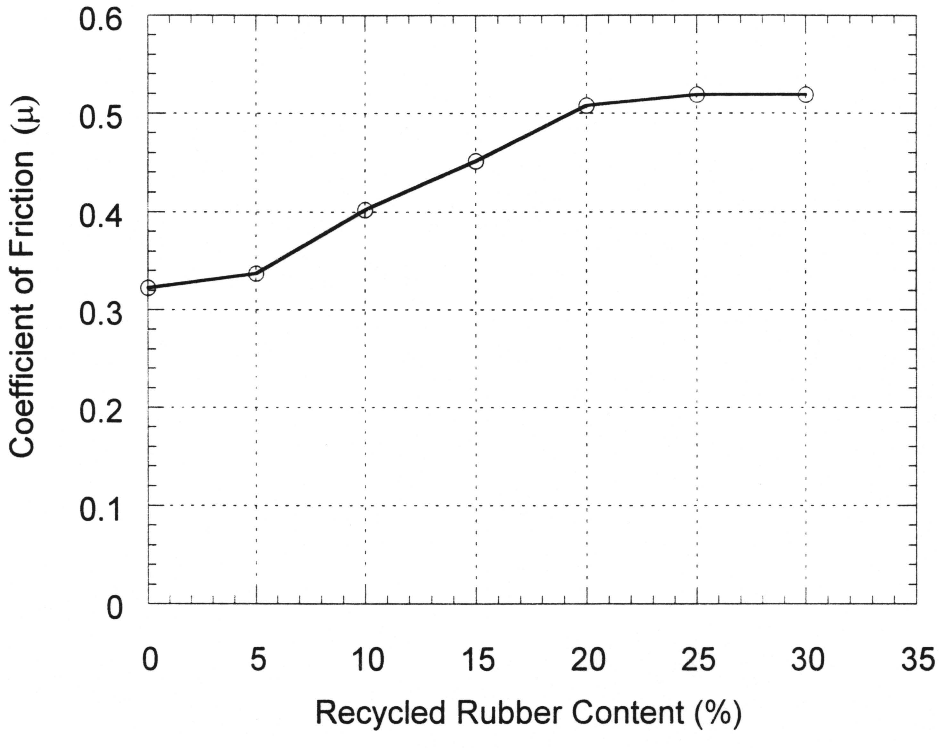

Fig. 13 Coefficient of friction as a function of recycled rubber content in composites of recycled HDPE with recycled rubber

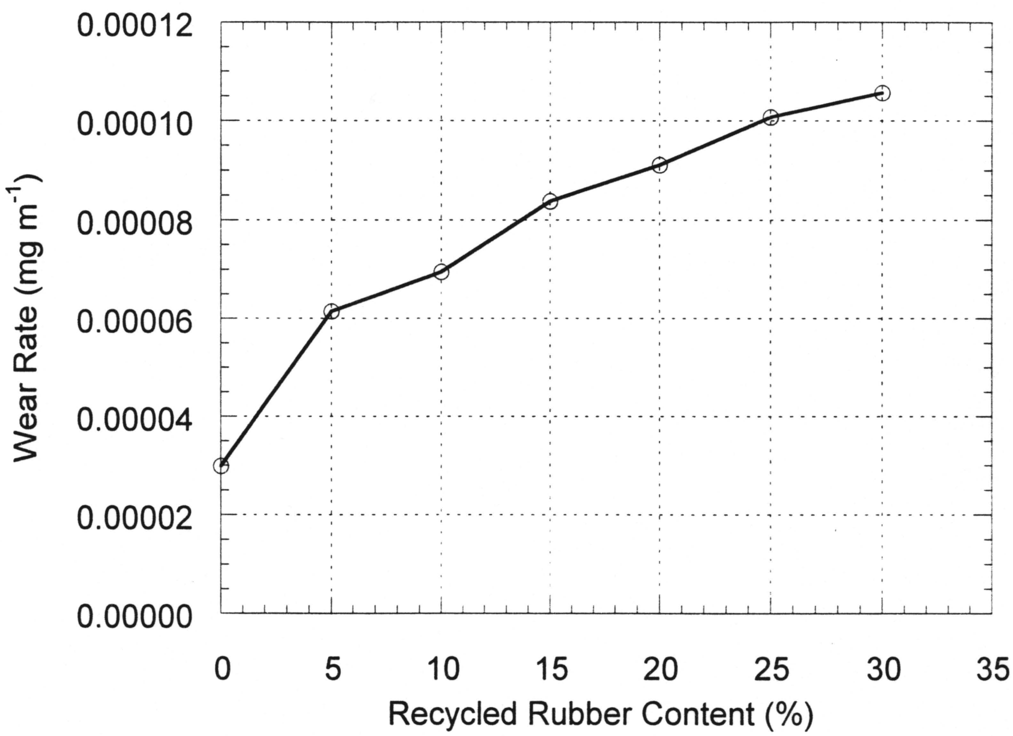

Fig. 14 Wear rate as a function of recycled rubber content of composites of recycled HDPE with recycled rubber

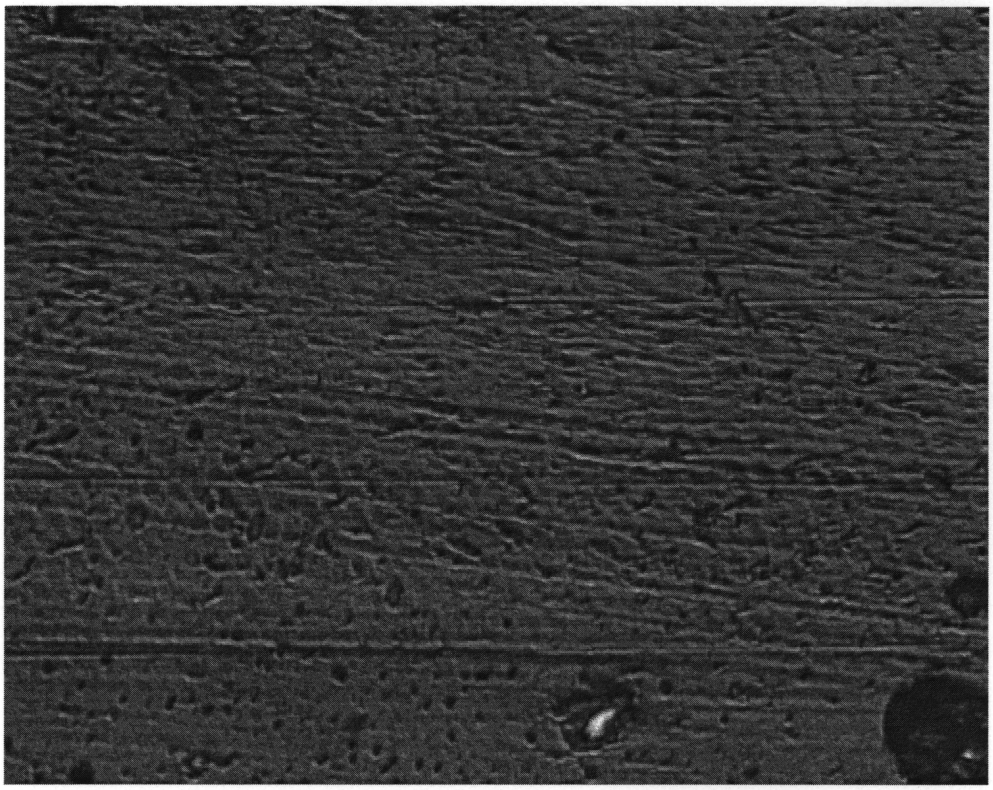

Fig.15 Micrographs of wear surfaces of composites of recycled HDPE with recycled rubber after 1 hour friction and wear testing at a sliding speed of 15.10 m s^{-1} and a normal pressure of 16.46 MPa: (a) 10% recycled rubber; (b) 20% recycled rubber; (c) 30 % recycled rubber (243.3 X)

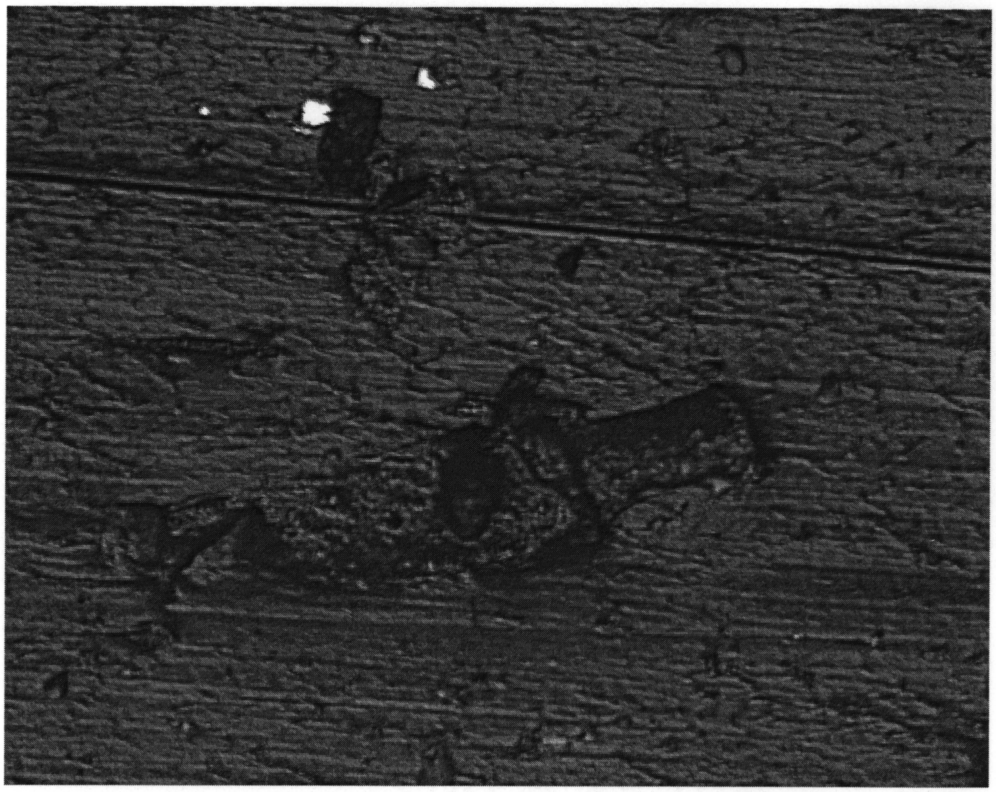

Fig.15b

Fig.15c

rubber content. It is evident that the increased rubber content severely weakened the material.

Figure 15c is a micrograph of the surface of recycled HDPE with 30 percent recycled rubber. This picture was taken after 1 hour of testing with a sliding speed of 5.10 m s^{-1} and a normal pressure of 16.46 MPa. The increased rubber content further weakened the material. Severe damage has occurred to the surface, which is evident due to the removal of rubber particles that were once bonded with the HDPE.

Figure 16a is a micrograph of the cross section of recycled HDPE with 10 percent recycled rubber. This specimen was tested for 1 hour testing with a sliding speed of 5.10 m s^{-1} and a normal pressure of 16.46 MPa. A thin layer of material deformation is seen toward the wear surface of the specimen. The diagonal grooves in the picture were from specimen preparation.

Figure 16b is a micrograph of the cross section of recycled HDPE with 30 percent recycled rubber. This specimen was tested for 1 hour of testing with a sliding speed of 5.10 m s^{-1} and a normal pressure of 16.46 MPa. In this picture the depth of sliding induced deformation on the material has increased due to increased rubber content. This is because the increased rubber content drastically weakened the material.

As can be seen from the results in this section, both coefficient of friction and wear rate increased with increased recycled rubber percentage. Increased recycled rubber percentage caused more severe damage on the surface because it weakened the material. Moreover, increased recycled rubber content resulted in a thicker subsurface deformation layer.

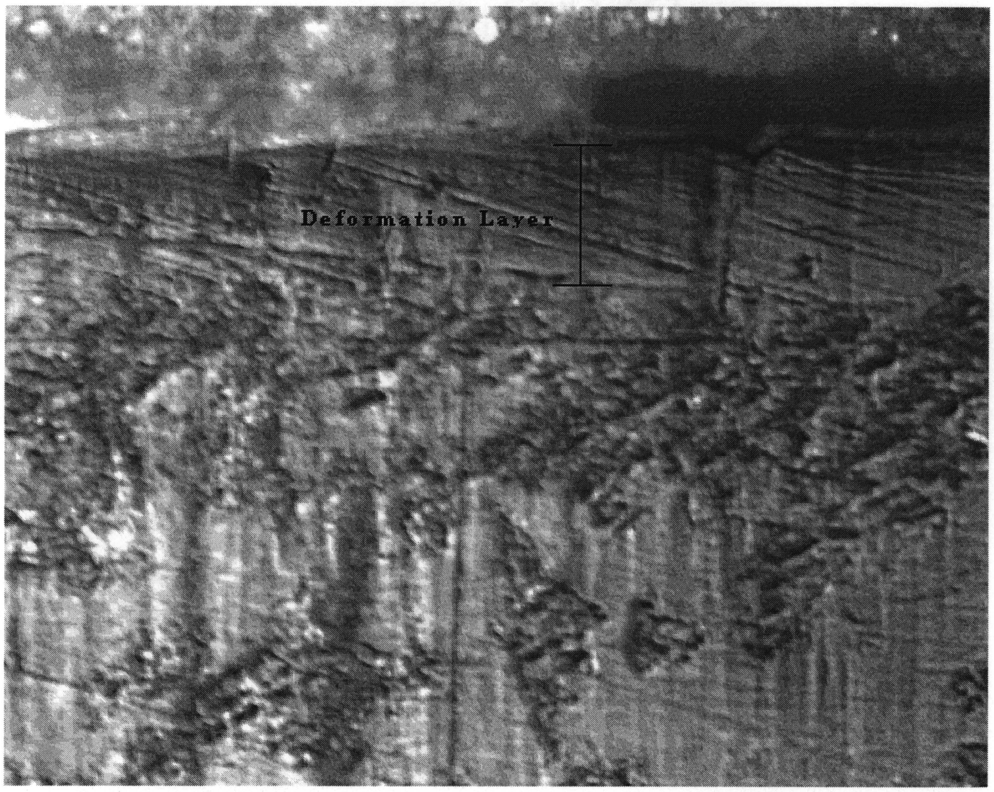

Fig.16 Cross section of composites of recycled HDPE with recycled rubber after 1 hour of friction and wear testing with a sliding speed of 15.10 m s^{-1} and a normal pressure of 16.46 MPa: (a) 10% recycled rubber; (b) 30% recycled rubber (243.3 X)

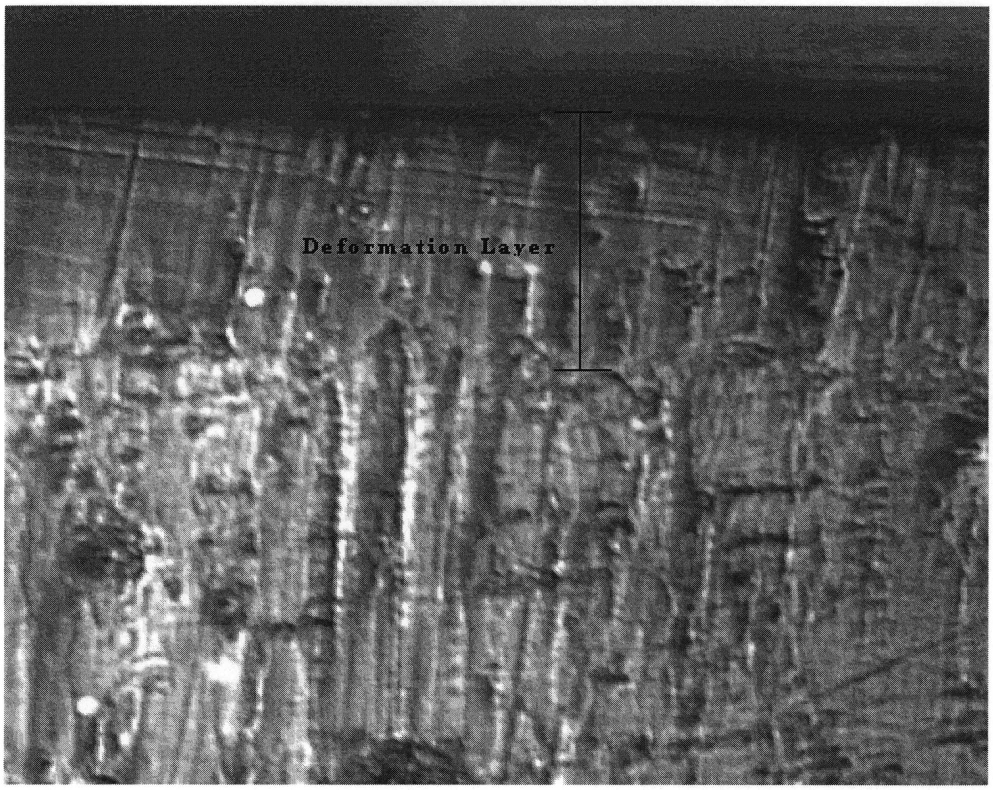

Fig.16b

CHAPTER V

CONCLUSIONS

After the study on the mechanical and tribological properties of composites containing recycled HDPE and recycled rubber, the following conclusions were made.

1. The tensile strength of composites containing recycled HDPE and recycled rubber decreased as the rubber content increased.

2. The ductility of composites of recycled HDPE with recycled rubber drastically decreased when rubber content increased to 5 percent, and further decreased gradually from 5 to 30 percent.

3. The hardness of composites of recycled HDPE with recycled rubber decreased as the rubber content increased.

4. The impact strength of composites of recycled HDPE with rubber decreased drastically at 5 percent recycled rubber. When the content of recycled rubber was from 5 to 25 percent, impact strength remained fairly constant, and then decreased further as rubber content increased to 30 percent.

5. Coefficient of friction and wear rate increased as the sliding speed increased for composites of recycled HDPE with 5 percent recycled rubber.

6. Coefficient of friction and wear rate increased as the normal pressure increased for composites of recycled HDPE with 5 percent recycled rubber.

7. Coefficient of friction and wear rate increased as the recycled rubber percentage increased in composites of recycled HDPE with recycled rubber.

8. Surface damage increased as sliding speed, normal pressure, or percentage of recycled rubber increased.

9. The depth of subsurface deformation decreased as the sliding speed increased, while the depth increased with increasing normal pressure and rubber percentage.

RECOMMENDATION FOR FURTHER STUDY

1. Research the effects of different sliding surfaces on coefficient of friction and wear rate on composites of recycled HDPE and recycled rubber.

2. Research the effects of different surface finishes on coefficient of friction and wear rate on composites of recycled HDPE and recycled rubber.

3. Research the effects of different processing temperatures on coefficient of friction and wear rate on composites of recycled HDPE and recycled rubber.

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