Development of Recycled Plastic Composites from Consumer Electronic Appliances

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Abstract

Consumer Electronic Appliances (CEAs), such as computer and printer housings, are composed of different types of plastics that can be recycled through collection, identification, and sortation. Typical CEA plastics such as acrylonitrile butadiene styrene (ABS), polystyrene (PS), polycarbonate (PC), and PC/ABS blends are thermoplastics, which have the potential to be used for future applications, such as recycled plastic lumber. A handheld Fourier Transform Infrared (FTIR) spectrophotometer was brought to a plastic de-manufacturer to identify and sort different types of plastics found in the recycled CEA waste stream. These plastics were then blended in different compositions with high density polyethylene (HDPE), a relatively inexpensive and lightweight plastic that offers great durability, through injection molding. The mechanical properties of each sample were then tested in tension and impact; in the samples tested, greater strength and resistance was shown by increasing the composition of PC and ABS in HDPE. The overall data analysis confirms that blends of CEA plastics and HDPE could potentially be utilized in the plastic lumber industry.

1. Introduction

Recently, plastics derived from CEA’s have attracted attention for their applicability in the recycled plastic lumber industry. Plastics from CEAs present a possible replacement for traditional materials such as steel and wood. The primary goal of this research is to evaluate the mechanical properties of various plastic composites and determine their potential in the recycled plastic lumber industry; the CEA plastics were collected from Tech Recycling de-manufacturer. The amount of each plastic identified at the de-manufacturer is included [Figure 1].

Plastic materials including Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), Polystyrene (PS) and a PC/ABS blend were collected and tested in this research. From the plastic obtained from Tech Recycling, 67% was ABS, 21% was PC, 5% was PS, 1% was PC/ABS, and 6% were different plastics not used in this research. Each of these plastics was mixed with High Density Polyethylene (HDPE) to potentially enhance the mechanical
properties of HDPE. HDPE is the predominant material used for plastic lumber due to its durability, low cost, and ubiquity.\textsuperscript{3}

The specific purpose of this research is to evaluate and analyze the mechanical properties of various plastic materials. FTIR was used to identify the composition of the plastic materials obtained from Tech Recyclers. Each type of plastic was granulated, dry blended with HDPE at various concentrations, and processed through injection molding. Tensile testing was conducted to evaluate the effect of CEA plastic reinforcement on HDPE. This method of testing determines the modulus of elasticity, yield strength, strain at yield, and ultimate tensile strength.\textsuperscript{4}

Analyzing the mechanical properties of plastic composites can give insight to the variety of potential applications recycled plastics may have in the plastic lumber industry. As compared with traditional materials like steel and wood, CEA plastic composites offer enhanced durability since they are not subject to corrosion and offer environmental benefits.\textsuperscript{2} Overall, the purpose of this research is to determine the potential recycled CEA plastics have in the expanding plastic lumber industry.

2. Background

Polymers are long chains of monomers, which are individual components covalently bonded to one another. There are natural and synthetic polymers; synthetic polymers are typically derived from oil and natural gas. Polymers can be further categorized as either thermoplastics or thermosets.\textsuperscript{5} Thermoplastics can be heated and molded multiple times and are recyclable.\textsuperscript{5} In contrast, thermosets can be heated and molded only once, thus, they are not recyclable.\textsuperscript{5}

As polymers, plastics possess various compelling qualities, such as the ability to be easily processed and recycled, along with being relatively cheap.\textsuperscript{5} Plastics are either semi-crystalline or amorphous.\textsuperscript{5} Semi-crystalline plastics have disordered and ordered regions.\textsuperscript{5} Properties that increase with crystallinity include opacity, rigidity, and tensile strength.\textsuperscript{5} Amorphous plastics’ molecular structures are often arbitrarily arranged.\textsuperscript{5}

The plastics industry prospers due to its low cost, flexibility in manufacturing and compelling qualities.\textsuperscript{5} The cost of plastic composites is lower than that of steel and the weight of plastic composites is lower than that of steel and aluminum.\textsuperscript{3} Plastic composites are materials made up of two or more constituents, which typically possess different chemical and physical properties.\textsuperscript{5} A plastic composite is usually made of a polymer matrix and a reinforcing agent.\textsuperscript{5} Commonly used reinforcing agents include fiberglass, carbon fibers, carbon nanotubes, mica, and rubber.\textsuperscript{5, 6, 7} Plastic composites have varying thermal, mechanical, electrical and optical properties. By determining the thermal properties of plastic composites, one is able to determine the necessary processing conditions, optimize the material properties, and determine appropriate applications.

Thermal properties that are usually tested include melting point and glass transition point.\textsuperscript{8} The melting temperature is the temperature at which the crystalline regions become molten or liquid-like.\textsuperscript{8} Glass transition is the temperature at which molecules are free to move and slide past one another.\textsuperscript{8} Semicrystalline polymers have a glass transition and melting temperature, while amorphous polymers only have a glass transition temperature.\textsuperscript{8} Semicrystalline polymers are processed above their melting temperature, and amorphous polymers are processed above their glass transition temperature.\textsuperscript{8} Mechanical properties need to
be determined for plastic composites in order to successfully determine appropriate applications.

In order to discern the mechanical properties of plastic composites, the American Standard Test Methods (ASTM) must be adequately followed. Common tests measure loading situations in terms of tensile, compression, flexural and shear forces. Data obtained from these tests are presented in force versus displacement curves and stress versus strain curves. These graphs allow one to determine the modulus, ultimate strength, stress at fracture, strain at fracture, and toughness.

Viscoelasticity is another crucial trait of a polymer. A viscoelastic polymer displays both viscous and elastic properties under deformation. Its response to a stress load is dependent upon its chemical structure, morphology, size of the applied load, rate or time period of loading, and temperature. If the material is more elastic, the energy is stored in deformed bonds, meaning the material can return to its original shape. However, it may exemplify a viscous response, where energy is dissipated in flow and molecules slide past one another, resulting in no elastic recovery and plastic deformation.

Plastic processing is relatively inexpensive due to lower temperatures and less energy required as compared to other industrial processes. Additionally, there is a lot of flexibility in manufacturing applications due to the ability to make lots of shapes for various uses. Compounding is a common practice which involves combining a base plastic resin with other components; this process makes the base resin perform better, cost less, process more easily, look more attractive, and improve other characteristics. Types of plastic processing include extrusion, blow molding, injection molding, intrusion molding, and compression molding. The temperature for processing must be above the glass transition and melting point temperatures.

Nearly 30% of all globally produced plastics are developed via injection molding [Figure 2]. The four stages of injection molding include clamping, injection, cooling in a specific mold, and ejection. The injection phase of the injection molding process includes placing pellets of plastic materials or blends of plastic materials into the machine. The plastic material is then melted by a combination of heat and pressure, which is injected into the mold afterwards. The third phase, cooling, encompasses the molten plastic cooling inside the mold once it contacts the interior mold surface. As the molten plastic slowly cools, it takes the shape of the mold. The final phase of injection molding, ejection, is ejecting the cooled plastic from the mold after a sufficient amount of time has passed. Following the injection molding process, additional processing may be required. The pressure for injection molding must be high enough to force plastic through the nozzle and into the mold; additionally, the RPM rate can affect mixing.

A common method of determining the type of plastic in a sample is done through Fourier Transform Infrared Spectroscopy (FTIR Spectroscopy). Essentially, infrared radiation is absorbed and transmitted through a sample; when this radiation interacts with the molecules of the sample, it absorbs energy and vibrates faster. The specimen of this sample is then analyzed through the library infrared spectrum of absorption peaks and vibration frequencies. The corresponding peaks and vibrations of the specimen and documented plastic help to determine the amount of which plastic is present and thus, its identity [Figure 3].
2.1 Materials

There are myriad plastics that are utilized for consumer electronics. However, not all plastics can be recycled.

Polyvinyl chloride (PVC) is an unusable plastic due to its harmful chlorine content along with its inability to be incinerated, therefore occupying space in landfills.

The main plastics used in this experiment are PC, ABS, PC/ABS blends, HDPE, and PS.

2.2 PC

PC is a polymer composed of Bisphenol A (BPA) monomers. It is a transparent plastic commonly used to produce a variety of products, including shatterproof windows, digital media, medical devices, electronic equipment, and eyeglass lenses. PC is formed by condensation polymerization; this is the polymerization of one or more monomers resulting from the elimination of small molecules. Condensation polymerization between BPA and either a carbonyl chloride or a diphenyl carbonate results in the PC polymer. PC is part of the polyester category of plastics. Unique properties of PC include its high impact strength and transparency. PC is one of the most widely used thermoplastics, particularly in the field of engineering, due to its various beneficial qualities, including that it is environmentally friendly and recyclable. The primary application of PC is in the optical media market, although PC is also often used in computers. Global demand for PC is nearly 1.5 million tons.

PC is amorphous and thermally resistant up to 135°C. It can be processed by injection molding, structural foam molding, extrusion, vacuum molding, and blow molding. Additionally, PC is commonly used in polymer blends primarily due to its compatibility with other polymers. PC is often used in a blend with ABS to encompass the polymers’ best qualities. PC/ABS blends possess unique qualities such as high toughness at low temperatures and high melt flow. PC/ABS blends further have high ductility and impact strength at temperatures below those of pure PC. PC’s chemical structure consists of repeating C₆H₉O₃ monomers, shown below.

PC Monomer

- [ O - C - C | O - C ] -

Figure 4: PC Monomer

2.3 ABS

ABS is a terpolymer, which is a polymer made of three monomers. Different grades of properties can be achieved through different percentages of each component. ABS is a thermoplastic and is amorphous, with a glass transition temperature of 105°C. Additional mechanical properties of ABS include its impact toughness and resistance. ABS has moderate heat, chemical, and moisture resistance, limited weather resistance, and flammability with high temperatures. The lightweight nature of ABS allows applications in household and consumer goods, such as small kitchen appliances and toys (e.g. Lego Bricks), whitewater canoes, and drain-waste-vent pipe systems. ABS is composed of a combination of three monomers in different proportions: the Acrylonitrile monomer (C₃H₃N), Butadiene monomer (C₄H₆) and the Styrene monomer (C₈H₈), as shown below.
2.4 **PC/ABS Blends**

PC/ABS blends are made by combining PC and ABS in manners such as Injection Molding (IM). Commonly used in computer housing, PC/ABS blends have interesting properties that vary by percent composition of each material. A higher concentration of PC increases the Young’s Modulus and results in a higher stress at fracture. A low percentage of PC results in a large percent strain at fracture, as does a high percentage of PC. However, a blend containing 20-80% PC has a small percent strain at fracture. A similar result is found for the impact strength for the same interval of composition. A PC/ABS blend has similar properties to both PC and ABS, except it is usually stronger, tougher, and more durable. PC/ABS blends are also resistant to both hot and cold temperatures, moisture, and creep, which is the permanent deformation due to a continuous stress.

2.5 **HDPE**

Polyethylene is a commonly produced polymer in the US. HDPE is a recyclable thermoplastic made from petroleum with a large strength-density ratio. It has a variety of applications, including soda bottles, fireworks, and plastic lumber composites. At a worldwide market volume of 30 million tons in 2007, HDPE is the second most widely used plastic in the world. As compared to Low Density Polyethylene, HDPE has higher intermolecular forces and a higher specific strength. HDPE is preferred in packaging over glass, metal and cardboard due to its durability, resistance to heat, and light weight. HDPE is composed of the ethylene monomer, which is shown below and has a chemical formula of C\(_2\)H\(_4\).
3. Methods

3.1 FTIR

Fourier Transform Infrared (FTIR) is a common method of infrared spectroscopy used to identify unknown materials and to determine the components of mixtures. Samples of FTIR Spectra Graphs for ABS, PC, PC/ABS and PS are included [Figures 8-11]. 20.9 kg of plastic were previously analyzed with a handheld FTIR machine, identified, and sorted at the de-manufacturer, Tech Recycling [Figure12].

3.2 Injection Molding

Injection molding is a method commonly utilized to process thermoplastics and thermosets; it is the preferred method for processing plastic parts, primarily because of the inexpensive operational cost of injection molding despite its high initial price. This molding process was utilized to make all the plastic samples for this experiment. There were 17 samples processed. Blends of 0, 10, 20, 30, 35, and 40 % CEA plastics in HDPE were tested, for which the CEA plastic component was either PC, ABS PC/ABS, or PS.

3.3 Tensile Test

Tensile testing determines tensile properties, such as ultimate strength and modulus, of dogbone-shaped plastic specimens. A plastic specimen is held by two clamps, and these clamps stretch the specimen apart until a breaking point has been reached. An extensometer is used to measure the elastic deformation of the specimen during the procedure. The load versus deflection is recorded, from which stress-strain curves and tensile mechanical properties are derived. Each of the samples’ specific measurements of width, thickness, and gage length were taken into account when calculating these tensile property values. The specimen must break within the middle gage length, or the data will be discarded. Five specimens were tested for each sample.

3.4 Impact Testing

Impact testing measures the strength of a material against brutal forces. A pendulum arm swings and hits the material at a designated notch; the energy absorbed during impact is measured and evaluated in terms of strength of the plastic specimen. An Intron Dynatup POE 2000 was utilized for impact testing. The notching is prepared 40 hours prior to the testing so that the clamps can secure onto the notch of the specimen. For each sample, ten plastic specimens were tested.

4. Results and Discussion

The results of tensile testing are shown in Figures 1-23. Results for tensile modulus, tensile yield, and tensile break points were analyzed. HDPE was regarded as the control of the composites tested, with the goal to create a CEA Plastics-reinforced HDPE composite with enhanced properties as compared with HDPE alone.

4.1 Tensile Modulus Results

Young’s modulus refers to the ratio of the tensile stress to the tensile strain in the linear region and is essentially a measure of the stiffness of a material. Higher modulus values indicate higher stiffness. HDPE achieved an average modulus of 1.22 +/- 0.07 GPa. The tensile modulus retains relatively similar values with increasing composition of PS [Figure 13]. The modulus was between 1.44 and 1.55 GPa for the first three concentrations of PS-HDPE. As for the PC-HDPE blend tested, the modulus slightly increased with increasing composition of
PC; the values ranged from 1.42 to 1.54 GPa [Figure 17]. When analyzing the data of the ABS-HDPE samples, the samples’ moduli increase along with increasing composition of ABS [Figure 21]. The modulus values obtained for the ABS-HDPE blend ranged from 1.30 to 1.58 GPa. When PC-ABS was blended with HDPE and tested, the modulus exemplified an increasing trend, with a slight decrease for the 30% (PC-ABS)-HDPE sample [Figure 25]. The values for this blend’s moduli ranged from 1.40 to 1.60 GPa. All of the samples’ moduli were comparatively greater than HDPE’s average modulus value. The highest modulus strength was shown by the 40% (PC-ABS)-HDPE sample. This gives insight to its ability to handle more tensile stress and exhibit rigidity than the other samples.

4.2 Tensile Yield Results

Tensile yield point describes the point at which the material deformation changes from elastic to plastic deformation. Prior to the yield point, elastic deformation can be recovered after load removal. After the yield point, plastic deformation cannot be recovered after load removal. At yield, HDPE’s average stress load was 21 +/- 0.1 MPa, while the strain percentage reached an average of 12.4 +/- 0.36%. The PS-HDPE blend’s stress at yield remained at 22 (+/-1) GPa while its strain decreased with increasing PS composition; the strain percentage values of PS-HDPE ranged from 11.01% to 6.07% [Figure 14]. As for PC-HDPE the stress at yield values slightly increased with increasing PC composition [Figure 18]. It had values from 22 to 27 GPa. However, the strain percentage values tended to decrease, encompassing declining values from 10.13% to 6.04%. The ABS-HDPE blend had slightly increasing stress values and rapidly decreasing strain percentage values [Figure 22]. The blend maintained an average of 22 GPa strain with a decreasing set of percentage values from 10.4% to 3.99%. When PC-ABS was mixed with HDPE the blend exemplified similar trends to their original components (PC and ABS); there were slightly increasing stress values along with dramatically decreasing strain percentage values [Figure 26]. The values for the stress at yield ranged from 23 to 26 GPa, while the values for the strain percentage at yield decreased from 10.18% to 3.97%.

4.3 Tensile Break Results

Tensile break point indicates the point at which the specimen fractured. All of the samples, including PS-HDPE, PC-HDPE, ABS-HDPE, and (PC-ABS)-HDPE, were observed to have the same trend in their respective tensile break plots. With increasing concentration of their respective CEA plastic, the stress increased while the strain percentage decreased. A decreasing percent strain at fracture can indicate a decrease in a material’s ductility. The virgin resin, HDPE, had an average stress load of 16 +/- 0.3 MPa with a strain percentage average of 49.88 +/- 6.62%. For PS-HDPE the stress at break increased from 16 to 21 MPa, and the strain percentage decreased from 236.13% to 8.64% [Figure 15]. The blend of PC-HDPE had stress values at break that increased from 17 to 27 MPa; the strain percentage values decreased 122.79% to 6.37% [Figure 19]. In Figure 18, the stress values of ABS-HDPE at break increased from 15 to 22 MPa, and its strain percentage values rapidly decreased from 64.01% to 4.91% [Figure 23]. When PC and ABS were blended together to mix with HDPE the values of stress at break ranged from 17 to 24 MPa; the strain percentage values at break decreased from 53.52% to 4.12% [Figure 27]. The (PC-ABS)-HDPE had its stress maximum at 30% PC-ABS;
there was a quick decline from 30% to 35% PC-ABS, then another steady incline. This leads to the implication that 30% PC-ABS has optimal ultimate strength over higher concentrations of PC-ABS in HDPE. PC-HDPE exemplified the ability to retain most stress while also allowing the highest % strain at fracture.

4.4 Stress-Strain Results

Stress-strain curves convey the modulus value, ultimate tensile strength value, stress at fracture, strain at fracture, and toughness of a plastic specimen; they indicate the tensile properties of each sample of recycled plastic composites. Stress is the force per unit area and strain is amount of deformation that a material experiences.

Stress-strain curves, comparing each plastic composite sample to HDPE, were developed to convey the tensile properties evaluated during tensile testing. The stress-strain curve comparing the properties of the various samples of PS-HDPE to the control sample of HDPE indicates that amount of stress experienced by all samples was relatively similar and varied between 21 and 23 MPa [Figure 16]. However, the amount of strain at which each sample fractured varied; PS-HDPE composites with 35% and 40% PS composition fractured earlier than other samples. This demonstrates that increasing the percent composition of PS in the PS-HDPE composite, the amount of strain withstood decreases.

The stress-strain diagram depicting the samples of PC-HDPE in comparison to HDPE conveys that the amount of stress experienced by all the samples differed between 20 and 28 MPa [Figure 20]. 30%, 35%, and 40% PC-HDPE samples were able to experience the most of amount of stress. 10% PC-HDPE was able to withstand the most amount of strain in comparison to other samples. This signifies that PC-HDPE plastic composites with higher percent compositions of PC can withstand less strain than those with lower percent compositions of PC.

The stress-strain curve comparing ABS-HDPE samples to that of HDPE signifies that stress experienced was between 21 and 23 MPa [Figure 24]. 10% ABS-HDPE withstood the most amount of strain in comparison to all other samples. ABS-HDPE samples with percent compositions of 20%, 30%, 35%, and 40% ABS were able to withstand the least amount of strain before fracture. This indicates that ABS-HDPE plastic composites with higher percent compositions of ABS withstood more stress, but withstood less strain before fracture.

Finally, the stress-strain diagram comparing (PC-ABS)-HDPE samples indicates trends found in the previously mentioned stress-strain diagrams. (PC-ABS)-HDPE samples with 30%, 35%, and 40% (PC-ABS) experienced the most stress, but withstood the least amount of strain before fracture [Figure 28]. The amount of stress for the samples varied between 20 and 25 MPa. The maximum strain withstood before fracture was experienced by 10% (PC-ABS)-HDPE. This further demonstrates that (PC-ABS)-HDPE plastic composites with higher percent compositions of (PC-ABS) can withstand more stress than strain.

4.5 Shortcomings

Problems were encountered when testing 35% (PC-ABS)-HDPE. The specimens repeatedly broke at the grips or immediately following the removal of the extensometer. Through careful observation, a stress concentration at the location of the entry of the mold was found on all the specimens. This was due to a failure to heat the mold during production, which caused improper flow of the molten plastic. Due to this, the specimens broke in the grips, and
data needed to be collected again. Additionally, the 35% and 40% PS-HDPE samples had faulty data; therefore, we have to return to obtain the correct data for 35% and 40% PS-HDPE again.

5 Conclusion

Recycled CEA plastic composites are a potential alternative in the plastic lumber industry. Plastics developed from injection molding were tested for their mechanical properties by tensile testing. Tensile testing allowed for the determination of which recycled plastic composite is most viable for the plastic lumber industry in terms of overall mechanical properties. Analysis of the results from tensile testing indicates that (PC-ABS)-HDPE is the most promising candidate as a recycled CEA plastic composite to be used in the plastic lumber industry. (PC-ABS)-HDPE had the highest modulus value and withstood the most stress and strain. Based on analysis of its mechanical properties, (PC-ABS)-HDPE has potential in the plastic lumber industry. This research contributes to the growing interest in developing alternatives to wood and steel. The plastic lumber industry currently utilizes plastic composites as alternatives to the more traditional materials. However, recycled plastic composites derived from CEA show potential in the plastic lumber industry.

This research demonstrated that recycled plastic composites, such as (PC-ABS)-HDPE, are able to be used in the plastic lumber industry. Axion International, Inc., a major company invested in the plastic lumber industry, strives to utilize recycled plastic composites for railroad ties and bridges. Essentially, analysis of the mechanical properties of recycled plastic composites, particularly tensile testing, allows for the determination of appropriate applications. Recycled plastic lumber poses various advantages such as being environmentally friendly and reducing the amount of waste produced. Future work related to this research includes flexural testing and analysis of thermal properties to further understand the properties of recycled CEA plastic composites.

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7 Resources


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## Appendix

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Figure 1: Plastics collected from Tech Recycling de-manufacturer

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### Injection Molding

![Injection Molding Diagram](image)

Figure 2: Injection Molding Single Screw Extrusion

www.substech.com
Figure 3: FTIR absorption spectrum

Figure 8: FTIR Spectra graph showing the unknown sample in red and the best match from the library in blue for ABS
Figure 9: FTIR Spectra graph showing the unknown sample in red and the best match from the library in blue for PC.

Figure 10: FTIR Spectra graph showing the unknown sample in red and the best match from the library in blue for PC/AB.

Figure 11: FTIR Spectra graph showing the unknown sample in red and the best match from the library in blue for PS.
Figure 12: HandheldFTIRunit
Figure 13: Tensile Modulus Plot corresponding to PS-HDPE blends

Figure 14: Tensile Yield Plot corresponding to PS-HDPE blends
Figure 15: Tensile Break Plot corresponding to PS-HDPE blends

Figure 16: Tensile Stress-Strain Curve corresponding to PS-HDPE blends
Figure 17: Tensile Modulus Plot for corresponding PC-HDPE blends

Figure 18: Tensile Yield Plot for corresponding PC-HDPE blends
Figure 19: Tensile Break Plot for corresponding PC-HDPE blends

Figure 20: Tensile Stress-Strain Curve corresponding to HDPE
Figure 21: Tensile Modulus Plot for corresponding ABS-HDPE blends

Figure 22: Tensile Yield Plot for corresponding ABS-HDPE blends
Figure 23: Tensile Break Plot for corresponding ABS-HDPE blends

Figure 24: Tensile Stress-Strain Curve corresponding to HDPE
Figure 25: Tensile Modulus Plot for corresponding (PC-ABS)-HDPE blends

Figure 26: Tensile Yield Plot for corresponding (PC-ABS)-HDPE blends
Figure 27: Tensile Break Plot for corresponding (PC-ABS)-HDPE blends

Figure 28: Tensile Stress-Strain Curve corresponding to HDPE