Assessing the Mechanical Properties of Recycled High-Density Polyethylene by Incorporating Various Compositions of Recycled Polypropylene

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Abstract: High-density polyethylene (HDPE) has unique characteristics, including ease of formation, lightweight properties, and corrosion resistance. Approximately 17% of all plastic produced globally is HDPE. However, its use contributes to environmental problems such as pollution and resource depletion. One way to address this issue is by recycling HDPE waste. Unlike previous research on HDPE, this study focuses on researching the mechanical properties of recycled HDPE combined with recycled polypropylene (PP). Several different HDPE-PP compositions were studied, with one of them being a blend of 95% HDPE and 5% PP. The mechanical properties investigated included hardness, Young's modulus, and impact strength. This research aims to provide valuable insights into managing HDPE plastic waste.
Keywords: Environmental problem, HDPE, plastic waste, polypropylene, mechanical properties, recycling

I. Introduction

Plastic is widely used in the packaging industry as beverage containers. The choice of plastic as a beverage container is due to its special properties such as lightness, transparency, ease of shape, low cost, stretchability, and high strength [1].

The specific properties of these materials result in their widespread use and plastic production increases along with technological developments. The plastic-making process is made from hydrocarbons sourced from petroleum, and fibers from plants and animals.

other hand, the increasing use of plastic will cause environmental problems due to plastic waste which is difficult to recycle [2]. According to the United States Environmental Protection Agency (EPA) in 2018, 35.7 million tons of plastic waste were generated in the United States, 12.2% of total municipal waste (MSW). Then approximately 27 million tons of plastic (18.5% of U.S. plastic waste) are thrown into landfills, and only about 4.5% of plastic packaging is recycled [3].

One alternative to reduce dependence on the original material of plastic products, as well as to reduce the consequences of the increasing plastic waste is to recycle the plastic waste [4],[5]. Recycling plastic waste will reduce the production of these materials, and at the same time protect the surrounding environment from pollution [6].

The recycling of plastic waste without harming the environment has been proposed by several researchers (Maitlo et al. 2022). Sousa argued that traditional destruction such as burning and stockpiling plastic waste in the soil is not good for the surrounding environment, therefore it is recommended to use the in-line reforming pyrolysis process that converts plastic waste into hydrogen gas using microwave heating [7]. In line with Sousa, Mentes also argued that there are several ways to change plastic waste into energy-generation materials. However, there will be several not simple processes that must be performed in the heating process [8]. Théoden emphasized the importance of implementing strategies to recycle and reuse plastic waste to reduce its negative environmental impact. Currently, the common approach is the mechanical recycling process, and it is supplemented with other approaches even though it is still in the testing stage, namely the use of chemical substances [9]. However, it should be noted that a specific process needs to be carried out to recycle plastic waste. It is necessary to learn various things first, including looking at the types of plastic that can be recycled [10], [11], [12]. One type of plastic that is generally recycled is high-density polyethylene (HDPE) which is a type of polymer that is widely used in the manufacture of detergent bottles and containers [13]. HDPE is a type of thermoplastic that is relatively easy to recycle compared to other plastics. Around 17% of the world's plastic production is HDPE [14]. HDPE is commonly used for containers, including chemical pipes, wrapping of industrial products, electrical insulation, household appliances, and bottles [2]. HDPE is also used to material products such as flower pots, traffic barrier cones, golf bag liners, water drain pipes, stadium seats, soft drink bottle caps, and toys [15]. In addition, HDPE is the most suitable material for the manufacture of floating structures for the placement of solar photovoltaic (PV) systems due to its lightweight and excellent mechanical and chemical resistance properties [16].

Because polymers have so many uses, the study of thermoplastic composites has received great attention in recent years [17]. So, it is always relevant to discuss. Hapuwatte stated that because of the heavy use of HDPE, understanding the optimal allocation of limited HDPE recycling yields must be done to achieve broader sustainability goals. Therefore, research related to the allocation of recycled HDPE materials needs to be carried out, namely from the life of the products produced. [14].

Blanco focuses his research on the mechanical recycling process of HDPE plastic waste, and he argues that the biggest challenge of this recycling process is the mixing of a significant percentage of HDPE with another plastic material, namely PP (polypropylene) [18]. The compound of HDPE plastics with PP will greatly affect the quality of the materials in the recycling process. [19]. Blanco's opinion was also echoed by Khabbaz who stated that mixing HDPE and PP resulted in changes in the quality of recycled HDPE plastic [20],[21]. In addition to Blanco and Khabbaz, Zhang also investigated the degradation of HDPE quality during recycling. [22], [23].

The effect of mixing other materials on HDPE plastic so that it reduces quality after recycling has also been researched by several more researchers. One of them is de Sousa Felix, who studied the effect of mixing polylactic acid (PLA) with HDPE products to be recycled (de Sousa Felix et al., 2024). Felgel-Farnholz argues that in the process of mechanical recycling – i.e. sorting, pre-processing, and remelting of plastic waste – there must be a gradation in the quality of the resulting recycled plastic. This occurs because different varieties of plastics may be unintentionally mixed, particularly during the sorting process. Therefore, it is necessary to get another approach such as analytical techniques [24].

The statements of Blanco, Khabbaz, Zhang, and other researchers regarding quality degradation are understandable because recycling implementation requires several steps before producing recycled plastic that can be processed into new products [25]. One crucial step in recycling is to sort the different types of plastics beforehand. A simple and widely practiced method is sorting by density. This method causes the mixing of PP with HDPE. This is because PP has the same density as HDPE.

Based on the results of the studies discussed above, studies related to thermoplastics are still very relevant to discuss. Then to better understand the problems correlated to HDPE and PP in more depth, this paper aims to identify the mechanical properties of high-density polyethylene (HDPE) before and after the HDPE is recycled and mixed with polypropylene (PP) in various compositions. This paper is different from previous studies because it focuses on the existence of various HDPE-PP compositions to understand the mechanical properties of recycled HDPE. The mechanical properties discussed in this paper refer to hardness, Young's modulus, and impact strength.

II. Material and Methods

2.1. Preparation of samples and test specimens

Sample preparation requires several steps to obtain the materials used: pure HDPE materials, recycled HDPE, and recycled PP. Pure HDPE is in the form of granules, while recycled HDPE and recycled PP are in the form of sheets obtained from containers and must be ground before they can be produced as test specimens. The milling process uses a grinding machine called a granulator. This machine will grind the container into small pieces called flakes. The sample composition in this study is based on Table 1, with the mixing process to obtain the composition done manually.

Table 1: Composition of the research sample

100% pure HDPE (not recycled)
100% recycled HDPE + 0% recycled PP
97% recycled HDPE + 3% recycled PP
95% recycled HDPE + 5% recycled PP
92% recycled HDPE + 8% recycled PP
90% recycled HDPE + 10% recycled PP
88% recycled HDPE + 12% recycled PP
85% recycled HDPE + 15% recycled PP

After preparing the sample, the next step is to use the injection molding technique to manufacture the test specimen, namely by entering the composition based on Table 1 on the Ray-Ran Test Sample Injection Molding Apparatus, this is so that the resulting specimen is under ASTM standards.

Molding Apparatus, this is so that the resulting specimen is under ASTM standards. This injection molding technique was chosen because with this method the quality of the samples produced is better and easier when compared to other methods. The mold is pre-cleaned with a benzene solvent. HDPE in the form of granules or flakes is put into the reservoir. The section of the reservoir is typically surrounded by a heating coil. The heater serves two crucial functions in the injection molding process. First, it melts the polymer that has been placed into the reservoir. Second, it injects the melted material into the mold at the correct pressure and speed. The pressure range set for specimen preparation is 5 to 7 bars. The temperature range for the injection molding machine is 260º to 280º Celsius. Meanwhile, the molding temperature ranges from 60º to 90º Celsius. The mold is an essential tool for conducting hardness tests, impact tests, and tensile tests, ensuring the precision and accuracy of our assessments.

2.2. Testing equipment for data collection

The mechanical test carried out in this study aims to determine the desired mechanical properties, namely hardness, Young's Modulus, and impact strength. All of these properties can be known by conducting hardness tests, tensile tests, and impact tests. All tests and data collection are carried out directly using special equipment, namely Durometer Type D for hardness testing, Universal Testing Machine for voltage testing related to the Young’s Modulus, and Charpy Test Equipment for impact testing.

In the hardness test, the durometer needle used is a frustum cone type having a spring load of 822 g which is suitable for thermoplastic measurements. Before the analysis is performed, the temperature of the sample is set between 20º Celsius and 25º Celsius. The thickness of the specimen is 1/4 inch (6,125 mm). Meanwhile, the width and length of the test piece are 10 mm and 60 mm, respectively. The range of hardness measurements is between zero to one hundred values. Measurements were taken 10 times for each sample to obtain the accuracy of the analysis results.

The tensile test is essential in engineering because it helps us understand how a material behaves under a static load. It is the most commonly used mechanical test for assessing a material's strength and ductility. This test is conducted using a Universal Testing Machine. In this test, the specimen is gripped by machine clamps at the top and bottom. One of these clamping machines can move, while the other clamp is static. When the clamp moves, the specimen will be pulled and subjected to a certain load. The load is gradually increased until the specimen fails. When the specimen is subjected to a load, it also experiences elongation. During stress testing with the Universal Testing Machine, a test piece measuring 2.5 mm in thickness, 25 mm in width, and 116 mm in length is used. The gauge has a dimension of 46.68 mm in distance and 6.4 mm in width.

The impact test used in this study is the Charpy Impact Test. This test is performed to identify the amount of energy absorbed when the pendulum breaks the specimen. The energy value obtained through this test will show the toughness of the tested sample material. This test uses bar-shaped and notched specimens. The notch is made 1 mm to 2 mm deep and has an angle of 45 degrees or 60 degrees. The purpose of the notch made on the specimen is to ensure that the stress is concentrated in the notch area. The specimen is placed in the clamping vise horizontally and struck from behind the notch. This test can show a rough picture of the fracture characteristics of a sample material, whether brittle or ductile. In this study, the size of the test piece used has a thickness of 6 mm, a width of 10 mm, and a length of 80 mm.

III. Results and Discussion

3.1. Hardness

A hardness test is carried out to measure the hardness of a material. In addition, this test is also closely related to the material resistance to plastic deformation, which is measured in the durometer index or scale D. Figure 1 shows a graph of hardness to the percentage of PP that forms the HDPE-PP composition. The values for the hardness test were taken in three positions to obtain accurate values.

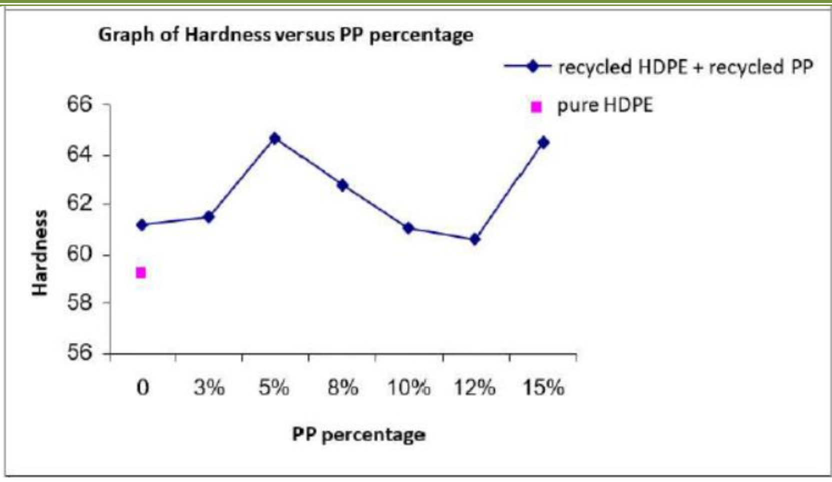

Figure 1: Graph of Hardness versus PP percentage

Based on the graph presented in Fig. 1, it is evident that the composition containing 5% PP and 95% HDPE yielded a hardness value of 64.666, which represents the highest hardness value among all compositions examined in this study. The hardness is at its lowest for the 100% pure HDPE composition, measuring 59.199. The hardness value increases when 100 percent recycled HDPE is used, resulting in a value of 61.199. If 3% of PP is mixed with 97% recycled HDPE, the hardness value will rise to 61.466. Then, if the composition is 5% PP with 95% HDPE, the hardness will improve to 64.666. However, in the composition of PP-HDPE mixtures of 8%-92% and 10%-90%, there was a decrease in hardness values to 62.733 and 61.066, respectively. Furthermore, an increase in the percentage of PP in the mixed composition will further reduce the hardness value, as evidenced by the 12% percentage, resulting in a hardness value of 60.599. However, it turns out that in the composition of PP-HDPE 15%-85%, the hardness value increases again to 64.466.

From the values obtained and after comparing each composition, it was found that the composition with the highest hardness value was a mixed composition of 5% PP with a value of 64.666. This shows that at a PPHDPE mixture content of 5%-95%, the material has the highest resistance to scratches or permanent dents when subjected to static loads. The hardness of 100% pure HDPE is the lowest at 59.199. Generally, it can be concluded that the hardness increases after the recycling process, whether it includes a PP mixture or not, compared to 100% pure HDPE material.

3.2. Young's Modulus

Tensile tests are performed to determine the values that can give mechanical properties such as Young Modulus, maximum load, maximum stress, maximum strain, breaking load, ultimate tensile stress, breaking strain, and elongation at break. In this study, the Young Modulus was chosen because the Young Modulus is the most important property for knowing the behavior of a material. Fig. 2 is a graph of the Young Modulus on the composition of PP content in the HDPE-PP mixture so that the influence of the PP percentage on the Young Modulus value can be identified.

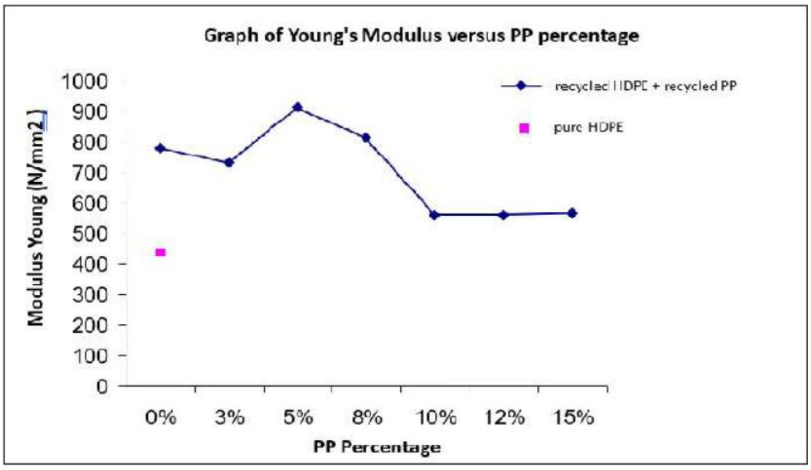

Figure 2: Graph of Young's Modulus versus PP percentage

Based on Fig. 2, the lowest Young's Modulus value for pure HDPE is 422.453 N/mm^2. This value can be increased if a material contains recycled HDPE mixed with recycled PP. Recycled HDPE without PP shows Young's modulus value of 778.725 N/mm^2. This value decreases if the composition of recycled HDPE mixture with recycled PP is 97%-3%, where the value is 728.29 N/mm^2. Furthermore, with a mixture composition of 95%-5%, the highest Young Modulus value was obtained, which was 908.032 N/mm^2. The increase in the percentage of PP mixture further shows a decrease in the Young Modulus value where the Young Modulus value in the 8% PP mixture is 808.869 N/mm^2 and the 10% PP mixture is 560.974 N/mm^2. Likewise, if the composition of HDPE-PP is at 88%-12%, then Young's modulus value drops to 560.232 N/mm^2. However, in the composition of HDPE-PP 85%-15%, the value of the Young Modulus slightly increased to 565,030 N/mm^2.

3.3. Impact Strength

The data value obtained from the impact test is the value for the impact energy in Joule (J). This value is converted into the impact strength value in J/mm2 through calculations. Fig. 3 shows a graph of impact strength on the composition of the HDPE-PP mixture.

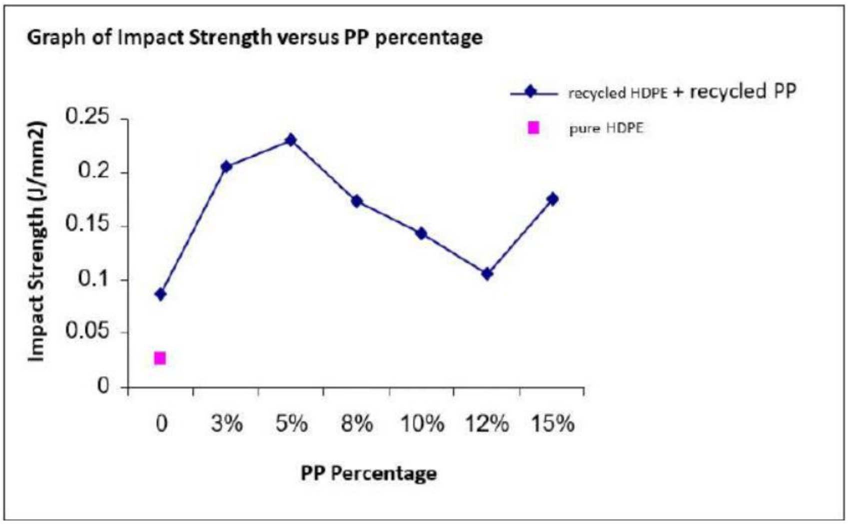

Figure 3: Graph of Impact Strength versus PP percentage

Based on Fig. 3, the impact strength for pure HDPE is 0.027 J/mm^2, and for 100% recycled HDPE the impact strength increases to 0.087 J/mm^2. The impact strength value will increase if recycled HDPE is mixed with recycled PP where in the composition of 97%-3% HDPE-PP mixing, the impact strength is 0.205 J/mm^2, and in the composition of 95%-5% the impact strength increases to 0.230 J/mm^2. The impact strength of the 5% PP composition is the highest value among all the compositions carried out in this study. Further data shows that if the PP percentage is increased at 8%, 10%, and 12%, there will be a decrease in the impact strength values to 0.172 J/mm^2, 0.1431 J/mm^2, and 0.105 J/mm^2, respectively. However, the impact strength value increased again to 0.174 J/mm^2 in the composition of 85%-15% HDPE-PP.

After conducting the impact test, it can be observed that the HDPE-PP mixture sample will display ductile fractures, whereas pure HDPE samples will exhibit brittle fractures. This brittle state will be minimized after pure HDPE undergoes a recycling process and is also combined with PP material. It should be understood that the impact strength indicates a state of crystallization closely related to the density of the material. Therefore, an increase in density will also lead to a rise in violence.

3.4. Comparison of each test on HDPE-PP composition

After conducting the tensile test, hardness test, and impact test, the effect of PP percentage on the mechanical properties of HDPE can be identified in terms of Young's Modulus, hardness, and impact strength. Table 2 shows the values of Young's Modulus, hardness, and impact strength based on HDPE-PP compositions.

Table 2: Relationship of composition to values of Young's Modulus, hardness, and impact strength

Composition	Young's Modulus (N/mm^2)	Hardness	Impact Strength(J/mm^2)
Pure HDPE	422.453	59.199	0.027
Percentage of recycled PP in recycled HDPE			
0	778.725	61.199	0.087
3	728.79	61.466	0.205
5	908.032	64.666	0.230
8	808.869	62.733	0.172
10	560.974	61.066	0.1431
12	560.232	60.599	0.105
15	565.03	64.466	0.174

Based on Table 2, it was observed that the mechanical properties of 100% pure HDPE are the lowest. In all of the tests, it was found that the mechanical properties of the recycled composition were higher than those of 100% pure HDPE. Specifically, the composition of recycled HDPE with a 5% PP mixture ratio showed the highest values for each test: 908.032 N/mm^2 for Young's Modulus, 64.666 for hardness, and 0.230 J/mm^2 for impact strength. The mechanical properties increase as the HDPE-PP composition changes from 100%-0% to 95%-5%, but decrease from 92%-8% to 88%-12%. However, at 85%-15% of the HDPE-PP composition, the mechanical properties increase again to 565.03 N/mm^2 for Young's Modulus, 64.466 for hardness, and 0.174 for impact strength.

After conducting all three tests, it is evident that the results of each test are interconnected. The values are affected by the composition of HDPE-PP. For instance, if the hardness value decreases, the impact strength and Young's Modulus values will also decrease.

IV. Conclusion

Based on the tests carried out, it is known that samples containing 100 percent pure HDPE show poor mechanical properties with hardness values of 59.199, impact strength of 0.027 J/mm^2, and Young's Modulus of 422.453 N/mm^2. The recycling process will not lower the mechanical properties of HDPE, on the contrary, the mechanical properties will be improved by adding PP at a certain percentage. The results of this study show that the mixed composition of 95% recycled HDPE with 5% recycled PP has the best mechanical properties where the hardness value is 64.666, the impact strength is 0.230 J/mm^2 and the Young Modulus is 908.032 N/mm^2.

The results of this study will have a positive impact in terms of a better understanding of HDPE plastic waste management. With this understanding, the plastic waste can be reused and environmental pollution due to the waste can be reduced.

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