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https://doi.org/10.5109/6782152

出版情報：Evergreen. 10 (1), pp.489-495, 2023-03. 九州大学グリーンテクノロジー研究教育センター
バージョン：

The Tensile Properties of Recycled Polypropylene Filament (rPP) as 3D Printing Material

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(Received September 6, 2022; Revised March 24, 2023; accepted March 24, 2023).

Abstract: Thermoplastic plastic waste, which comprises a significant portion of all plastic waste, has the potential to be repurposed through 3D printing techniques. Among the various types of plastic contributing to the plastic waste issue, Polypropylene (PP) plastic, commonly found in food packaging, is a major contributor. While recycling PP plastic poses certain challenges, it also presents a promising avenue for addressing the plastic waste problem. This study aims to evaluate the mechanical properties of 3D printed specimens fabricated from recycled Polypropylene (rPP) filament derived from post-consumer instant noodle packaging waste. The process involved shredding and extruding the packaging material into rPP filament, which was subsequently utilized to print dogbone samples in an FDM 3D printer at nozzle temperatures of 180°C, 190°C, 200°C, 210°C, and 220°C. In addition to others fabricated from commercial Polypropylene (PP) and Polylactic Acid (PLA) filaments, these samples were subjected to tensile testing to determine their ultimate tensile strength and Young's modulus. The results indicate that rPP filament printed at 210°C exhibited the highest average values for ultimate tensile strength and Young's modulus at 20.73 MPa and 806.35 MPa, respectively. These values were comparable to those of the commercial PP filament, though lower than those of the commercial PLA filament, which were nearly twice as high as the PP values. However, an increase in extrusion temperature was accompanied by an increase in the deviation of the testing results, suggesting that higher temperatures may result in an increased amorphous fraction in the rPP.

Keywords: tensile strength; recycled polypropylene filament; polylactic acid filament; dogbone sample; 3D printing

1. Introduction

Indonesia is among the top contributors of plastic waste globally, with plastic waste making up the top three types of waste produced[1-3]. Plastic packaging and bottles are the most common types of plastic waste in the country[3-5]. Polypropylene (PP) plastic, frequently used in food packaging, is a major contributor to the plastic waste problem[3,6–8]. Currently, most post-consumer PP is collected by garbage collectors and deposited in landfills[1,2]. Since plastic does not decompose quickly in landfills, innovative solutions are needed to reduce landfill accumulation. As a thermoplastic polymer, PP can be softened and molded through thermal processing methods, which are among the preferred methods for dealing with PP waste[6,8,9].

The 3D printing technique is a thermal processing method that exploits thermoplastic materials' ability to be quickly re-softened and molded into functional objects quickly[10–13]. The process of 3D printing involves heating the material to its melting point and constructing a physical model layer by layer[14–18]. Polypropylene plastic waste, which is also thermoplastic, has the potential to be processed using 3D printing[6,8,19–21]. However, it is uncertain whether the mechanical properties of polypropylene plastic waste will be degraded significantly during this process[8,17,22–24].

This study investigates the mechanical properties of polypropylene plastic waste[25], specifically the tensile properties of ultimate tensile strength and Young's modulus[26]. The polypropylene plastic waste used in this study is derived from the post-consumer packaging of Indomie, a popular instant noodle in Indonesia produced by PT. Indofood Sukses Makmur Tbk. The methodology of this paper will begin by outlining the process of transforming the raw material into filament, followed by a description of the 3D printing process and the preparation of the tensile test. The results of the study will be presented in the final section, followed by conclusions.

2. Methodology

The rPPs obtained in this study are processed from Indomie's plastic packaging as shown in Fig. 1. The food packaging was collected through a post-consumer plastic collection program conducted by PT. Indofood Sukses Makmur Tbk. The post-consumer plastic collection program educates the food stalls that sell the noodle to clean and separate the noodle's outer packaging waste made from PP and return the waste to the company. The collected post-consumer plastics were then shredded into small pieces using a conventional paper shredder, as shown in Fig. 2. The shredding process is repeated several times until the pieces are small enough, as shown in Fig. 3. and easy to be fed into the extruder machine[27].

Fig. 1: Indomie's plastic packaging.

Fig. 2: Paper shredder.

Fig. 3: Chopped product.

The extrusion process was carried out using a custom extruder machine located in the Laboratory of Vibration and Machine Maintenance, Faculty of Engineering, Universitas Sebelas Maret, shown in Fig. 4 below. The extruder is a single-screw extruder machine supported by a 1450 rpm motor drive with a 1:60 gearbox ratio. The heating system is an electric heater regulated by two temperature controller units divided into a set of barrel and nozzle heaters. The applied nozzle is 1.0 mm in diameter. The temperature for both heating systems was maintained at 185^{o}C during the extrusion.

Fig. 4: Extruder machine.

The extrusion process is carried out by inserting the chopped product into the extruder machine through the hopper. No additional materials nor additive is added to the hopper. The chopped product will be distributed by screw (inside the extruder machine) through the barrel, which is heated to the temperature of 180 ^{o}C by the heating system. Slowly the chopped plastic will change its shape into melted plastic. The end zone is the outlet nozzle of the extruder machine where the compression process occurs, and the melted plastic result will be pushed out through the outlet nozzle in rPP filament form. The output filament product of rPP is shown in Fig. 5 below. The result is a long filament with a diameter of about 1.3 mm. The filament's consistency is fairly good after about 1 meter of the first extrusion. Some irregularities existed mainly due to the impurities such as noodle crumbs, oils, etc.

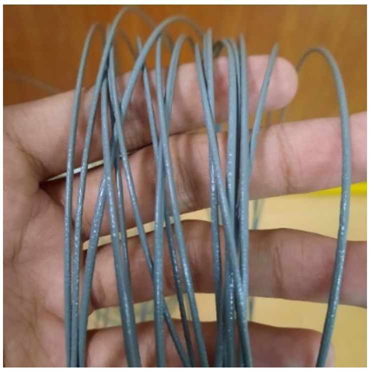

Fig. 5: Output filament by extrusion process.

The 3D printer machine used is Creality Ender-3 with a few modifications, such as the motor drive system replacement into a direct drive motor, supported by a chamber to maintain the ambient temperature around the machine to minimize the effects of warping shrinking during the printing process. The dogbone samples for the tensile test purpose referred to the type V of ASTM D638-14 standard[28]), shown in Fig. 6 below.

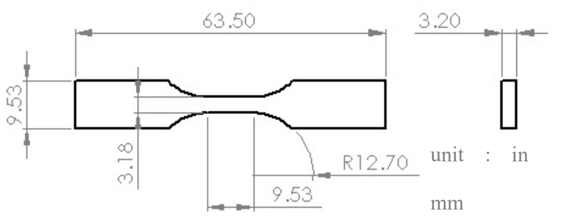

Fig. 6: The dimension of dogbone samples referred to the type V of ASTM D638-14 standard[28]).

The parameter settings of 3D printing used for the recycled Polypropylene (rPP), Polypropylene (PP), and Polylactic Acid (PLA) filaments are shown in Table 1 below. The rPP's nozzle temperature trials were selected based on the extruder machine's nozzle temperature setting on the extrusion process and commercial Polypropylene (PP) filament (KREAfil) processing temperature in 3D printing. Initially, the nozzle temperature was tested at the melting point of Polypropylene (160°C)[5]), but it had a low success rate. The same result was found at 170°C of nozzle temperature until it began to build a proper dogbone-shaped sample at 180°C. The summary of the printing trial matrix is shown in Table 2 below.

Table 1. Printing parameters for rPP, PP, and PLA filaments.

Parameters	**Values**
Nozzle diameter	1.0 mm
Layer thickness	0.32 mm
Infill degree	100%
Printing speed	20 mm/s
Bed temperature	80°C with an insulating layer (rPP and PP); 85°C (PLA)
Nozzle temperature	180°C, 190°C, 200°C, 210°C and 220°C (rPP); 210°C (PP); 215°C (PLA)

Table 2. Printing trial matrix.

		Nozzle diameter (mm)				
		0.4	**0.5**	**0.6**	**0.8**	**1.0**
Nozzle temperature (°C)	**160**	N	N	N	N	N
	170	N	N	N	N	N
	180	N	N	N	N	Y
	190	N	N	N	N	Y
	200	N	N	N	N	Y
	210	N	N	N	N	Y
	220	N	N	N	N	Y

Remarks : N = Failed
Y = Succeed

As a benchmark, the dogbone specimens printed from Polypropylene (PP) and Polylactic Acid (PLA), both coming from commercial-type filaments produced by KREAfil (PP) and Shenzen eSun Industrial Co. Ltd. (PLA), were prepared. Three (3) dogbone samples were prepared for each variant of rPP, PP, and PLA filaments. The rPP's printed samples were gained in gray color due to the color combination in Indomie's plastic packaging. The printed samples are shown in Fig. 7 - Fig.13 below.

Fig. 7: The rPP's printed dogbone samples of nozzle temperature at 180°C.

Fig. 8: The rPP's printed dogbone samples of nozzle temperature at 190°C.

Fig. 9: The rPP's printed dogbone samples of nozzle temperature at 200°C.

Fig. 10: The rPP's printed dogbone samples of nozzle temperature at 210°C.

Fig. 11: The rPP's printed dogbone samples of nozzle temperature at 220°C.

Fig. 12: The benchmark filaments made of PP.

Fig. 13: The benchmark filaments made of PLA.

The test was carried out using a Universal Testing Machine (UTM) called RAY-RAN Test Equipment in the Laboratory of MIPA Terpadu, Faculty of Mathematics and Science, Universitas Sebelas Maret, the tensile testing shown in Fig. 14 below. The test was operated at 10 mm/min of testing speed and 5000 kgf of loadcell capacity[28].

Fig. 14: Tensile testing of dogbone samples.

3. Results and Discussion

The tensile test results of dogbone samples made from rPP filament with nozzle temperature set at 180°C, 190°C, 200°C, 210°C, and 220°C, as well as commercial PP and PLA filaments in this study, are shown in Fig. 15 and Fig. 16 below.

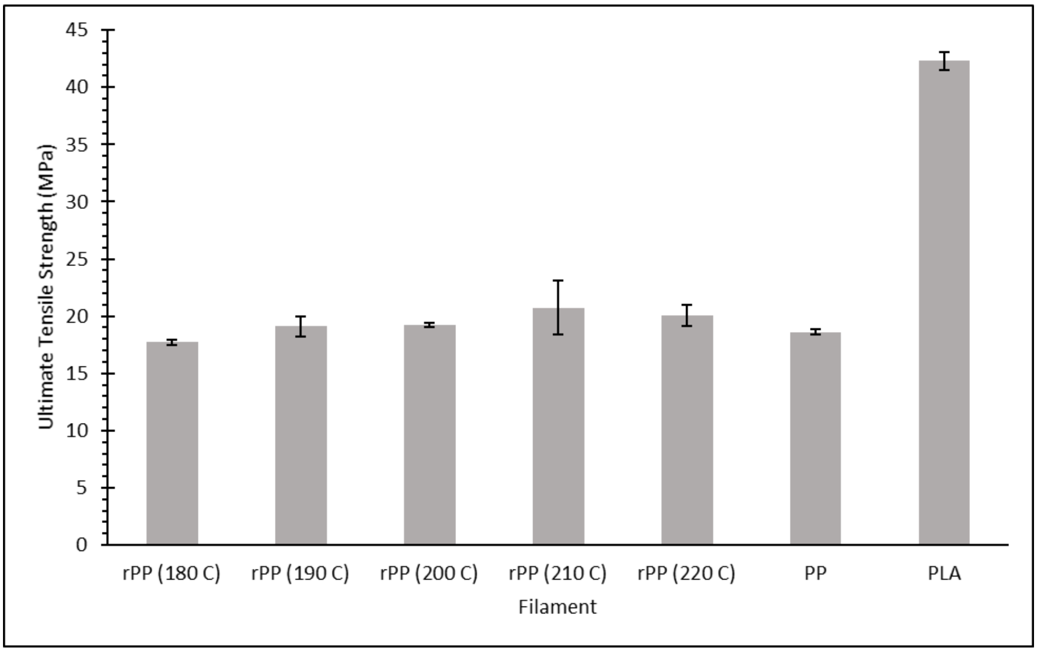

Fig. 15: Ultimate tensile strength of tested dogbone samples.

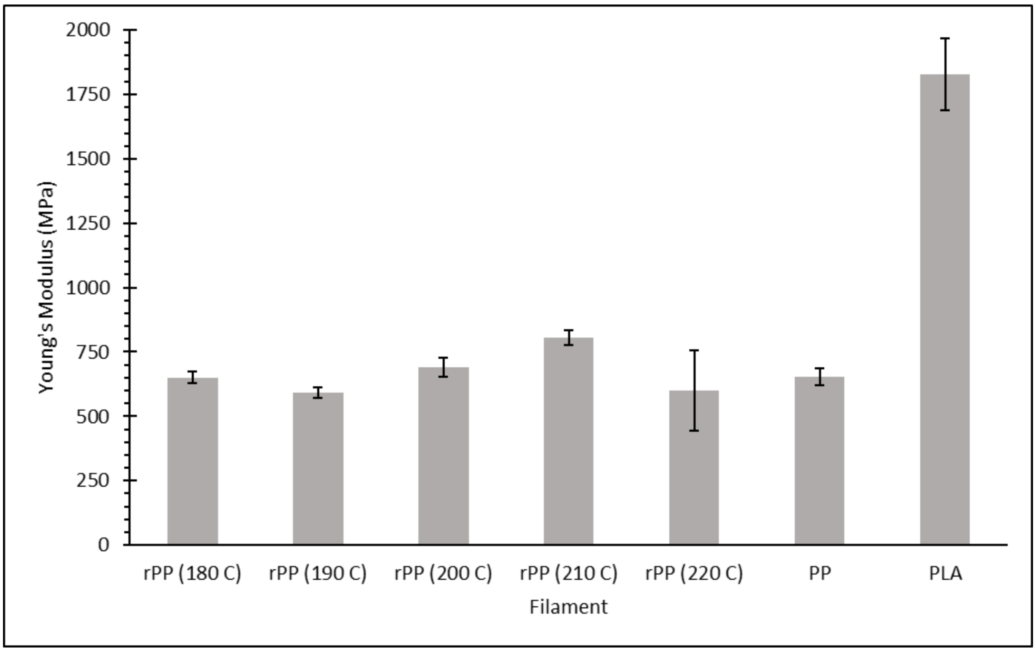

Fig. 16: Young's modulus of tested dogbone samples.

The highest value of Ultimate Tensile Strength (Fig. 15) and Young's Modulus (Fig. 16) among the dogbone samples made from rPP filament is 210ºC of nozzle temperature. These results strengthen the argument that the operating temperature of PP filament in 3D printing is at 210ºC[8], supported by the fact that the industrial standard PP filament has a standard operating temperature in 3D printing is also 210ºC. It can be concluded that printed rPP filament at 210ºC, compared to the value of tensile properties (Ultimate Tensile Strength and Young's Modulus), could replace the industrial standard PP filament by considering some limitations in the printing process.

The value of Young's Modulus on the rPP filament (180ºC) was seen to be higher than at 190ºC, so the modulus value decreased from 180ºC to 190ºC, then increased to its highest value at 210ºC. There is a difference from the Ultimate Tensile Strength value, which continuously increasing from 180ºC until its highest value at 210ºC. This anomaly was thought to be due to voids in the interior of dogbone samples made from rPP filament (190ºC). These voids are present due to the incompatibility of the infill degree value generated during the printing process compared to the infill degree value targeted in the digital slicing process. The presence of voids will affect the cross-sectional strength of the tested dogbone samples so that the tensile properties would decrease[8]. This study did not explain Polylactic Acid (PLA) filament further because it's only used as a benchmark, considering that PLA is a very common filament used in 3D printing. The discussion focused on comparing tensile properties by rPP and PP filaments.

4. Conclusion

In this study, a thermal processing method was utilized to transform the plastic packaging of Indomie instant noodles into a 3D printing filament. The resulting recycled polypropylene (rPP) filaments were then fed into a Fused Deposition Modeling (FDM) 3D printer to produce tensile test specimens in the form of dogbone samples. The dogbone samples were printed with nozzle temperatures of 180°C, 190°C, 200°C, 210°C, and 220°C and were subsequently tested in a tensile test machine to evaluate their tensile properties. The highest tensile properties were observed at a nozzle temperature of 210°C, with ultimate tensile strength and Young's modulus values of 20.73 MPa and 806.35 MPa, respectively. These results suggest that the rPP filament (210°C) may have the potential for interchangeability with standard polypropylene (PP) filament, given the comparable tensile properties obtained and limitations in the printing process.

An important factor to consider in this study is the printing condition used in the preparation of the dogbone samples. The 3D printer's nozzle produced dogbone samples with a diameter of 1.0 mm, resulting in a rough surface finish. While a smaller nozzle size may lead to improved surface quality, it also requires better filament processing with fewer impurities. In comparison, the standard nozzle size commonly used in FDM type 3D printing is typically 0.4 mm in diameter.

Acknowledgments

The authors would like to thank PT. Indofood CBP Sukses Makmur Tbk. for supporting this work under the collaboration project between PT. Indofood CBP Sukses Makmur Tbk. and Universitas Sebelas Maret.

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