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Investigation of Mechanical Properties of Recycled ABS Printed with Open Source FDM Printer Integrated with Ultrasound Vibration

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Abstract: Additive Manufacturing (AM) is a process that deposits materials on a platform to form 3D objects layers by layers. One of the downsides of AM is wastage generated during the printing process. Acrylonitrile Butadiene Styrene (ABS) is a popular material used in AM for thermoplastics. This study focused on the feasibility of using recycled ABS for the 3D printing process via an open source Fused Deposition Modeling (FDM) printer. The recycling process began by re-granulating the ABS waste and turning it into a new filament that used to print the test specimens. The experiment was carried out on the mechanical properties of the test specimens, and a comparison was made with the standard ABS specimens. The results showed that recycled ABS could be converted into filaments with an extrusion temperature of 270°C and a travel speed of conveyor at 18 mm/s. The results of mechanical properties showed recycled specimen had 32% and 28% reduction in flexural and tensile strength of the printed material, respectively, while an 82% increase in the compression strength due to multiple recycling cycles. With the aid of ultrasound vibration (20 kHz) onto the recycled ABS specimen, the results showed a 53% increase in flexural strength, 59% increase in compression strength and 19% increase in tensile strength comparing with 0 kHz of recycled ABS specimen. Overall, the recycled ABS waste is a viable option for better use of printed materials and, with the aid of ultrasound vibration, it helps to improve the mechanical properties of the recycled ABS.

Keywords: Mechanical Properties, Recycling, ABS, Fused deposition modeling, Ultrasound vibration

1. Introduction

Additive Manufacturing (AM) is a process that forms the 3D shape object through joining material and layer by layer approach, as opposed to subtractive methods of manufacturing [1] [2]. Fused Deposition Modeling (FDM) is one of the categories of AM. FDM is able to produce a functional part or prototype that are able to be used in various area such as automotive, electronics and electric devices, architecture and education [3] [4] [5]. AM is aimed at reducing waste materials. However, due to printing errors, it still creates a lot of waste material, as the inexperienced user frequently uses the standard FDM 3D printers. The amount of failed print is approximately 2.22 times the amount of predicted waste produced [6]. Therefore, the first concern is that too much waste is generated and the waste material needs to be processed or recycled.

Plastic waste introduced into the marine environment is a global issue. Plastic waste can be found all over the world, with concentrations of up to 580000 pieces per km2 and production increases exponentially [7]. Therefore, recycling waste material would reduce the amount of waste material. The FDM 3D printing process is not yet an environmentally friendly process, so an eco-printing has to be accomplished and researched.

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Mechanical properties of the recycled ABS were markedly degraded, resulting in a 13 to 49% decrease in the final strength of the printed material [8]. This is due to poor interlayer bonding, also known as delamination. Delamination can result from the weak matrix, poor lay-up or mechanical loading and often leads to internal damage in composites that could lead to global failure of a component with reduced strength and rigidity [9]. Hence to overcome the delamination, ultrasound vibration was introduced to improve the mechanical properties of the recycled ABS. ABS waste was collected, recycled and reproduced in a filament for an open source FDM printers. In contrast, few studies showed that ultrasound vibration was able to reduce surface roughness of 3D printed parts [10],[11]. However, lack of information regarding the effect of ultrasonic vibration to the mechanical properties of recycled ABS materials has been published.

2. Methodology

This methodology section describes the process of waste collection, ABS waste granulation process, filament extrusion, 3D printing process, and specimen test. The methodology includes detailed information, such as recommended granules size, appropriate parameters for extrusion filament, optimum parameters for printing ABS specimens, and optimum frequency for the ultrasound frequency. The SHIMADZU stress test machine was used for testing specimens to determine the flexural tests, tensile test and compression tests printed in 3D. Two different specimens were printed out, D790 for flexural test [12], D638-14 for tensile test and D695 for compression test [13]; both flexural strength compression strength was tested. 12 specimens for each test were printed with fixed orientation based on fixed nozzle temperature, bed temperature, printing speed, and raster angle and layer thickness. Conclusions was made based on the critical test results and analysis.

2.1 Waste Material for Acrylonitrile Butadiene Styrene

The waste ABS material was collected from the laboratory. The ABS waste material was separated from various materials to avoid material variability. Based on ABS standard 3D printing parameters, the ABS waste was cut into granules, filament and 3D extrusion molded.

2.2 Plastic Granulation

Mechanical recycling method was carried out to recycle the ABS waste [14]. Besides, the recycled ABS waste originates from the same batch, the same sourcing provider, and the same grade to ensure no restrictions or differences when comparing ordinary ABS filament with recycled filaments. There was no negligence in the test results this way. Residual ABS plastic was crushed and cut into smaller pieces using bench vice, hammer and wire cutter for the granulation process. It was compressed and crushed by using a torque generated by bench vice for waste ABS products bigger than $8cm^3$. Then use a wire cutter to cut the destroyed 3D ABS moulded product to make the desired size reduction and insert it into TW-SC 400F polymer crusher to produce the ABS. Filters with a 5 mm mesh size are used to separate large granular sizes so that uniformly sized sizes can be produced.

2.3 Generation of Filament

The next process was the filament generation of recycled ABS granules using the Haake Rheomex OS filament extruder. The filament extruder working principle is to place the granules in the funnel, and the drive screw fed granules into hot areas to dilute the granules. Following the softening and smelting of plastic granules, it was forced to flow through the heated nozzle at a constant temperature. The conveyor pulled the filament at constant travel speed after the filament was released from the heated nozzle to ensure that the diameter of the filament produced is the same as the desired diameter. The recommended filament diameters are 1.75 mm based on 3D FDM printer. The filaments produced by the filament extruder must be 1.75 mm so that the FDM 3D Filaments feeder can function correctly. The extrusion speed was set at 18 rpm, and the nozzle temperature and speed of the conveyor belt are adjusted to reach the diameter of about 1.75 mm.

2.4 FDM 3D Printing Process

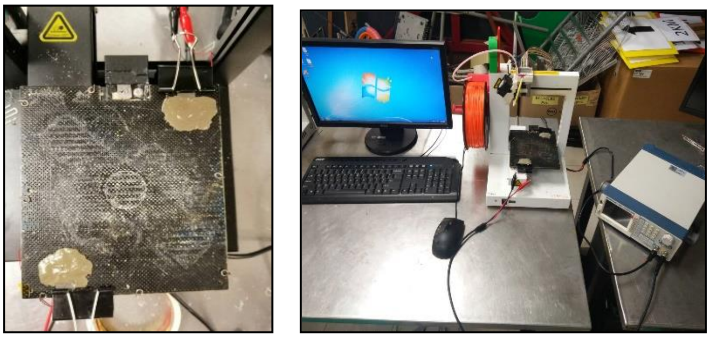
UP Plus FDM 3D printer was used to print the test specimen. The printing parameters such as extrusion temperatures, feed rate, and bed temperature need to be controlled to optimise 3D printed products. The feature of a heated printing platform is required to ensure good material adhesion during the printing process [15]. The raster angle and the thickness layer are set at optimum conditions. This is because the thickness of the lower layers will cause a finer surface roughness. Table 1 shows the standard 3D printing parameters for ordinary ABS filament, which is nozzle temperature of 235 °C and a bed temperature of 105 ° C for this study. The bed temperature will remain the same for the recycled ABS filament unless there is an adhesion problem between the layers. If the problem occurs, the parameters will be adjusted until there is no gap and adhesion to the 3D printable parts.

Table 1 - Parameters for the FDM machine

Type of Parameter	Value of Parameter
Nozzle temperature	235°C
Bed temperature	105°C
Printing speed	60 mm/s
Raster angle	30°
Layer Thickness	0.2 mm

2.5 FDM 3D Printing Process

The printer was set up with two piezoelectric transducers attach with a paper clip that provide ultrasound vibration (refer Figure 1 (a)). A function generator was used to provide 0, 10, 20 kHz of ultrasound frequency vibration through the piezoelectric transducers. The experiment set-up is shown in Figure 1 (b).



(a) (b)

Fig. 1 - (a) Set up of the piezoelectric transducer onto the UP-Plus machine; (b) Experiment set-up

2.6 Mechanical Properties Testing

To prove that the mechanical properties of the ABS recycling material will be improved using the ultrasound frequencies, it is necessary to define and compare mechanical properties. The flexural, tensile and compression tests were used to test the mechanical properties to determine the flexural, tensile and compression strengths of the material. The three tests were performed using the SHIMADZU AGS-X 20kN + 500 stress test system where three repeated measurements were performed. Therefore, it is necessary to print a total of 12 specimens for each of the testing by using an FDM 3D printing machine. In order to ensure the results of testing are correct, the test process should follow the standard test procedure. Different model types are printed to determine the recycled printability of ABS filament, and flexural and compression tests.

3. Result and Discussion

The results of ABS waste granulation, filament extrusion, 3D printed specimen, flexural test, tensile test and a compression test were discussed. There are 12 specimens printed for each test to measure their tensile strength, flexural strength and compression strength. The resulting tensile, flexural and compression tests were compared between the recycled ABS printed specimens and standard ABS printed specimens. In order to study the potential failure and mechanical properties of recycled ABS printed products, the results obtained were analysed and addressed.

3.1 Granulation

Plastic waste requires 4 to 5 repeated crushing cycles and processing through a 5 mm mesh sieve to obtain the size of the correct granules. Table 2 shows that the average granule size was approximately 4.28 mm, and the samples were examined over a maximum diameter/length of 4.27 mm. Even though the pallet size is larger than the commercial pallet size approximately by 1 mm, it still can be used to produce the filaments later on [16].

3.2 Filament Extrusion

Preliminary tests for extrusion temperature were set at 180°C and constant speed of 18 rpm but showed signs of filaments unable to extrude out smoothly and melt fracture occurred. This temperature was used as the lower limit of extrusion temperature, and an increase in temperature every 5°C, the quality of the filament is inspected to a maximum of 270°C. The temperature was increased to 270°C in order to get a smooth, round and tough recycled ABS filament. If lower than 270°C, the filament had rougher surface and inconsistent diameter.

After getting the most suitable temperature for filament extrusion, five different conveyor speed was tested to obtain the optimal filament diameter which is 1.75mm because it is the most suitable diameter to be used on the FDM machine. Figure 2 shows the graph of the average of extruder filament diameter changed against the conveyor speed for recycled ABS material. It can be seen that the recycled ABS show a decrease in the average filament diameter to increase conveyor speed. This is due to the pulling force acting on the conveyor belt, which affects the filament diameter. As a result, the increase in conveyor speed resulted in a decrease in the overall extrusion diameter.

Table 2 - The result of the size of 20 samples of ABS pellet recycled by using a blender

No.	Sample Size		No.	Sample Size	
	Length (mm)	Diameter (mm)		Length (mm)	Diameter (mm)
1	4.6	4.4	11	4.5	4.1
2	4.1	4.4	12	4.4	4.3
3	4.1	4.3	13	4.8	4.3
4	4.3	4.3	14	4.3	4.7
5	4.3	4.1	15	4.0	4.3
6	4.0	3.9	16	4.1	4.1
7	4.0	4.2	17	4.1	3.9
8	4.3	4.4	18	4.3	4.3
9	4.3	4.4	19	4.7	4.4
10	4.1	4.3	20	4.3	4.2
The average dimension of 20 samples				4.28	4.27

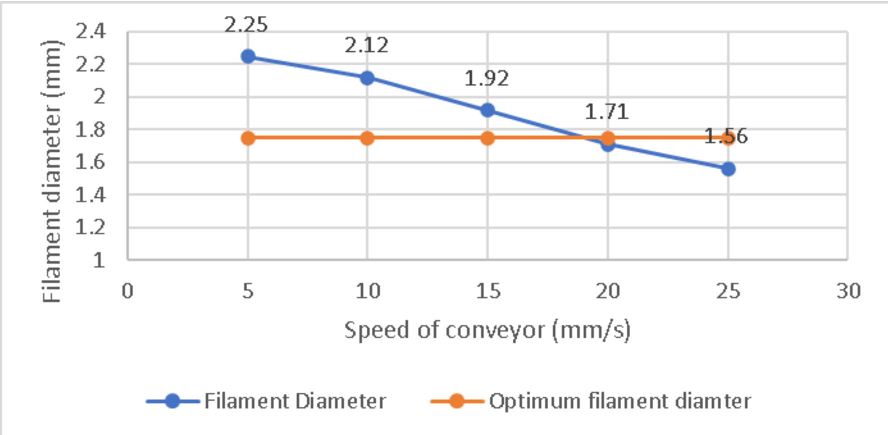


Fig. 2 - Graph of filament diameter (mm) against the speed of conveyor (mm/s)

3.3 3D Printing ABS Specimens

Examining the filaments using standard ABS, it was found that the printing quality was good, with optimal printing parameters including a nozzle temperature of 230°C, a printing speed of 60 mm/s (normal mode) and a bed temperature of 110°C. When the recycled ABS was printed in the same parameters, the resulting print showed defects in various form, as shown in Table 3. These issues were resolved by increasing the nozzle temperature 270°C, print speed reduced to 40 mm/s (fine mode) and bed temperature remained 105°C [17].

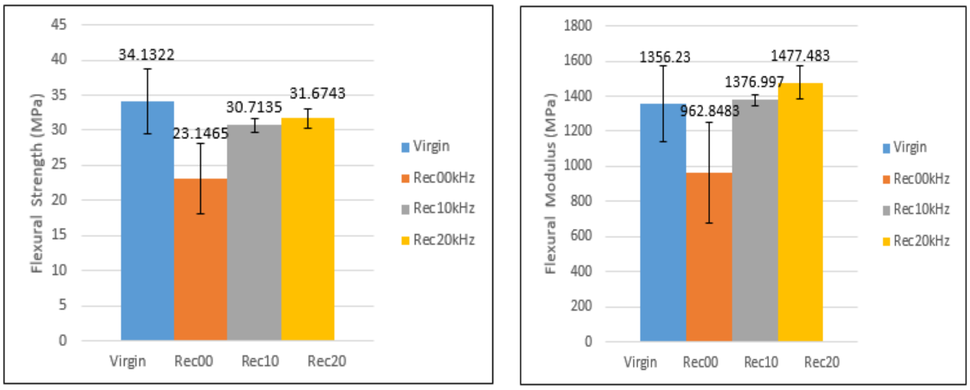
3.4 Flexural Tests

Figure 3 (a) and Figure 3 (b) offers a description of the complete flexural test data. It was found that by comparing the flexural strength between virgin and recycled filaments, there was a decrease in 32% with the 0 kHz frequency. Similarly, flexural modulus declined with an estimated decline of 29% with 0 kHz. Hence, these results indicate the mechanical degradation of the ABS plastic during recycling [18].

There was an increase in the flexural strength and modulus of recycled ABS filaments in 0, 10, and 20 kHz, an estimated 32% and 43% increased comparing between 0 kHz and 10 kHz, and an estimated 36% and 53% increased comparing between 0 kHz and 20 kHz. It was proved that according to this finding, with the aid of ultrasound vibration, the adhesion of recycled layers was greatly improved, which would work best for 20 kHz frequency samples. It was visually observed that the bending occurred by the test shows the crack for 20 kHz is much smaller than the 0 kHz.

Table 3 - Defects and solutions for 3D printing

Type of Defects	Cause of the Defects	Solutions
Under-extrusion	-The printing temperature is too low. -The filament is too small to extrude.	-Set higher printing temperature for recycled ABS filament. -Double-check the filament diameter (1.75mm).
Warping	-Material shrinkage -Bed temperature is low	-Applying solution mixed with acetone and ABS material -Heat build plate before start printing.
Broken Infill	-Wrong settings in the slicing software -Blocked nozzle	-Lower the printing speed -Clean the nozzle
Waves / Ripples	-The vibration of the machine -Fast printing speed	-Do maintenance on the machine -Reduce printing speed



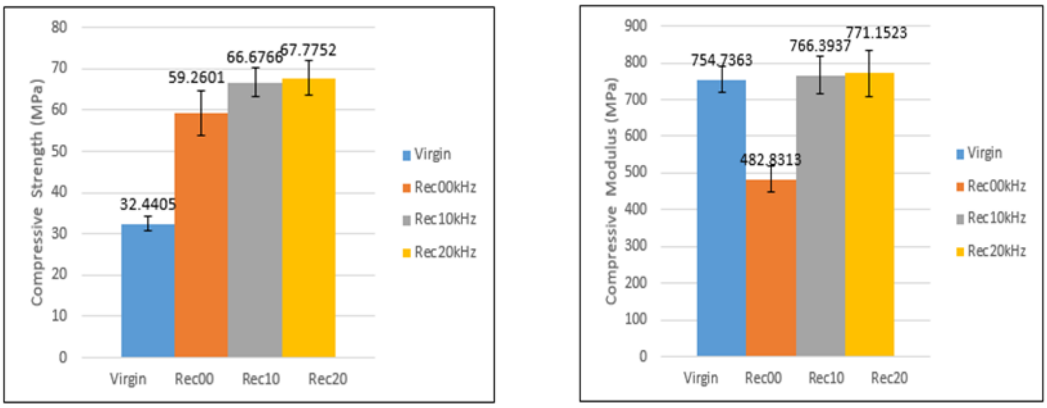
(a) (b)

Fig. 3 - (a) Comparison of Flexural Strength between the standard and recycled ABS printed specimen with different frequencies of vibration; (b) Comparison of flexural modulus between the standard and recycled ABS printed specimen with different frequencies of vibration

3.5 Compression Tests

Figure 4 (a) and Figure 4 (b) offers a description of the complete flexural test data. It was found that by comparing the compression strength between virgin and recycled filament, it improved by 82% with the 0 kHz. While compression modulus of recycled ABS that printed at 0 kHz was 36% lower than the standard ABS specimen. The compression strength result was increased due to the multiple recycling of the specimens. The mechanical properties of ABS improved when multiple recycling was done [19]. But the compression modulus for recycled ABS was still not as good as virgin ABS. This indicates the mechanical degradation of the ABS plastic during recycling [14].

There was an increase between recycled samples of 0 kHz, 10kHz and 20 kHz in terms of compression strength and modulus. There was a 12% and 58% increment at 10 kHz, and 14% and 59% increment at 20 kHz for compression strength and modulus respectively compare with the recycled ABS printed in 0 kHz. It was assumed that this finding represents the adhesion of recycled layers were stronger with the aid of ultrasound vibration, which 20 kHz would be the best frequency to improve the mechanical properties of the samples.



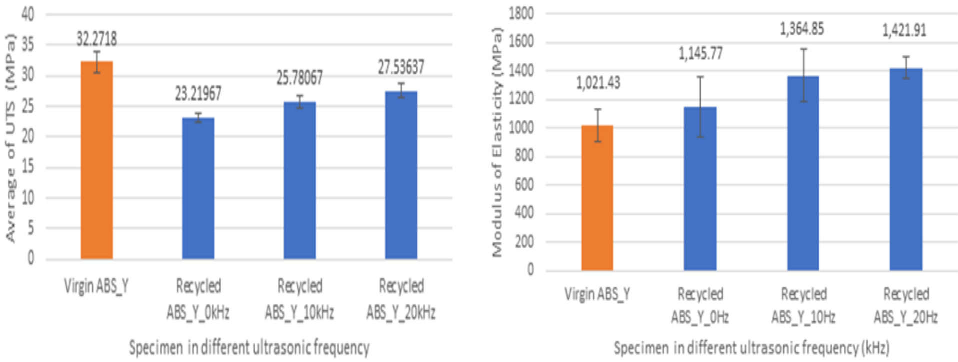
(a) (b)

Fig. 4 - (a) Comparison of compression strength between the standard and recycled ABS printed specimen with different frequencies of vibration; (b) Comparison of compression modulus between the standard and recycled ABS printed specimen with different frequencies of vibration

3.6 Tensile Tests

For the tensile test, there was improvement of tensile strength and modulus of elasticity for the recycled ABS specimen that printed with ultrasound vibration which is shown in Figure 5 (a). At 20 kHz of frequency, it had the greatest UTS (27.5363 MPa). Its UTS is 18.5907 % more than the UTS of recycled ABS specimen printed in 0 kHz of frequency. For 10 kHz, the UTS of the recycled ABS specimen was 25.7807 MPa, which was 11.0294 % greater than the recycled specimen printed with 0 kHz of vibration frequency.

Figure 5 (b) shows the comparison of modulus of elasticity between recycled and standard ABS specimen printed at different frequency of vibration. The result shows that the frequency of vibration at 10 kHz and 20 kHz can increase the MoE of recycled ABS specimen at 19.1208 % and 24.1014 %, respectively, compared to recycled ABS printed with 0 kHz of vibration frequency. When the frequency of vibration set at 20 kHz, it can greatly improve the MoE of recycled ABS specimen.



(a) (b)

Fig. 5 - (a) Comparison of tensile strength between the standard and recycled ABS printed specimen with different frequencies of vibration; (b) Comparison of modulus of elasticity between the standard and recycled ABS printed specimen with different frequencies of vibration

4. Conclusion

In this study, the methodology of reforming ABS waste into a relatively uniform 3D printer filament (1.76 mm) was achieved. When the filaments were formed, it was found that the extrusion temperature and speed of conveyor were important factors that would affect the diameter of the extruded filaments. The optimum temperature for the extrusion was 265°C, and the optimum conveyor speed was 18 mm/s. When involving mechanical recycling, it was expected there would be a degradation of recycled ABS due to heating. Hence, it was necessary to adjust the printing parameters to avoid defects occurred during printing. According to the results obtained for the mechanical properties of the recycled ABS, it showed that it had decreased, resulting in a 32% reduction in the flexural strength and a 28% reduction of the tensile strength of the recycled ABS printed specimen, while an 82% reduction in the compression strength. With the aid of ultrasound vibration, the results showed a 53% increase in flexural strength, a 19% increment of tensile strength and a 59% increase in compression strength comparing between the recycled ABS specimen that printed at 0 kHz and 20 kHz of vibration frequency. Overall, the approach to extrude recycled ABS plastics is a viable option for better use of printed materials and, with the aid of ultrasound vibration, it improves the mechanical properties of the recycled ABS. Therefore, this study shows tremendous potential for sustainable management of ABS waste through recycling, otherwise an increasing burden on resource and landfill sites. In addition, the cost of utilising the ultrasonic transducer to generate the ultrasound vibration to print the recycled specimen is small due to it could be purchased separately and attached to the printer.

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