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The Effect of Cooling and Temperature in 3D Printing Process with Fused Deposition Modelling Technology on the Mechanical Properties with Polylactic Acid Recycled Material

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Abstract – *3D printing is one of the most widely used manufacturing methods. However, its popularity also contributes to the worsening of the environment due to waste from leftover 3D print. Luckily, the usage of recycled filament has become more popular recently, but this recycled filament has lower mechanical properties. Because of that, their usage is less desirable. Therefore, this study aims to improve the mechanical properties of the recycled filament, especially Polylactic Acid (PLA), by one of the easiest methods controlling cooling factors on 3d print, such as fan cooling speed, extruder temperature, and bed temperature. This study uses a factorial design method to achieve the best combination level of fan cooling speed, extruder temperature, and bed temperature. From the study, the writers can conclude that the best factor combination based on both tests is fan cooling speed 100% (5 m/s), extruder temperature 190 °C, and bed temperature 50 °C, which is vastly different from the one recommended on PLA non-recycle. Furthermore, using this parameter, tensile strength has been improved as high as 37% and 5.3% on flexural strength.*

Keywords: *3D Printing Cooling, Factorial Design, Flexural Strength, Fused Deposition Modelling (FDM), Recycled Polylactic Acid (PLA), Tensile Strength*

Nomenclature

ANOVA	Collection of statistical models and their associated estimation procedures used to analyze the differences among means
CAD	Use of computers (or workstations) to aid in the creation, modification, analysis, or optimization of a design
FFF/FDM	3D printing process that uses a continuous filament of a thermoplastic material
PLA	Also known as Polylactic acid, is a thermoplastic polyester that is used as filament for 3d printing
PLA Non-recycle	PLA that is directly made from its raw material
PLA Recycle	PLA that is made from a recycled 3d print PLA waste
UTS	Ultimate tensile strength value that is gathered from tensile test
UFS	Ultimate flexural strength value that is gathered from flexural test

I. Introduction

Fused Filament Fabrication (FFF) printer, also known as Fused Deposition Modeling (FDM) [1], which is based on the material extrusion process [2], is additive manufacturing that can be described as an assembly of systems used to speedily manufacture or get together a scale model of a part using three-dimensional Computer Aided Design (CAD) information [3].

It is generally used in many industries including medical, and a variety of industrial applications for making models or prototypes to be analyzed in smaller scale and more easily [4], as it is also easily adapted to the needs for complex shape and by rescaling dimension [5]. Due to its price advantage, nowadays, the printer is used widely among makers [6].

However, 3D print popularity has also posed a problem for environmental concern due to printing waste in the form of plastic waste, especially from test prints, failed prints, and support structures [7]. Luckily the use of filament made from recycled plastic has been done before [8], [9], even though its usage is still minimal.

One of these filaments is Polylactic Acid (PLA). It is a thermoplastic made from starch (glucose) extracted from plants and converted into dextrose with enzymes so that PLA can be decomposed and recycled. However, composing PLA itself is tricky and takes a long time to decompose in nature [10]. Therefore, in dealing with waste from PLA, it is better to recycle PLA [11]. PLA filament itself, being thermoplastic, could be recycled into many things but the most interesting prospect is to recycle PLA filament back into new filament PLA recycle. PLA recycle itself is actually already available

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for consumer users.

However, the filaments from PLA itself have been degraded in terms of their mechanical properties [12], [13], making PLA recycle a less desirable material for 3D printing. Fortunately, it is possible to optimize the mechanical properties of 3d print results by tweaking deposition orientation [14]-[16], layer thickness [17]-[19], infill pattern [20], [21], printing speed [22]-[24], infill density [25], [26], cooling speed, and bed temperature as well as the extruder/print temperature. For example, lowering the cooling fan speed in the 3d print process using PLA non-recycled has been proven to increase the mechanical properties of the 3d print results by Lee and Liu in [27]. In addition, as the extrusion and the base temperature increase, there is also an increase in tensile and flexural strength [28], [29].

However, the crystallization temperature of PLA recycle is at a lower point than PLA non-recycle, as discovered by Fernandes in [30]. Therefore, the effects of cooling fan speed, bed temperature, and extruder temperature might give different results on PLA recycle than what discovered on PLA non-recycled. Thus, this paper aims to find those three parameters effects on PLA recycle, whether it is still the same or yields different results than its effects on PLA non-recycle.

Section I indicates the literature reviews of the research study. Section II explains mainly the parameters used and set-up before printing the samples. Section III contains the result of the printing itself, the tensile test and flexural test, and the analysis of the variance (ANOVA). Then the results have been discussed and compared to the previous study in section IV. Section V is the conclusion of the study

II. Parameters and Methods

The material for this experiment is a PLA recycle Biopolymer 4043D. The recommended temperature profile for extrusion and the bed temperature have been obtained from the material-technical datasheet, which will be used in this experiment. In addition, the fan speed to be used is at 0% and 100% (5 m/s). Based on this, all the parameters levels to be used are shown in Table I.

They could be made by a design experiment model, as shown below in Table II. The print result is in ASTM D638 Type 4 and ASTM D790 for tensile and flexural tests, respectively. Then the samples are printed according to the combination of parameters in Table II.

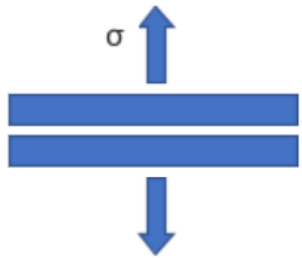
In order to obtain the bond tensile and the flexural strength between layers as Fig. 1(a) for tensile test and the flexural test as in Fig. 1(b), the print orientation has been made horizontally for ASTM D638 (Fig. 2(a)) and vertically for ASTM D790 (Fig. 2(b)).

TABLE I
FACTOR AND LEVEL TO BE USED

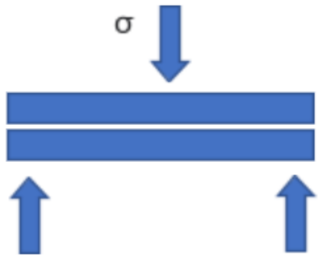
Factor	Level 1	Level 2
Fan Cooling (%)	0	100
Extruder Temperature (°C)	190	230
Bed Temperature (°C)	50	70

TABLE II
DESIGN EXPERIMENT MODEL

No.	Fan Cooling (%)	Extruder Temperature (°C)	Bed Temperature (°C)
1	0	230	50
2	100	230	70
3	0	190	50
4	100	190	50
5	100	230	50
6	0	190	70
7	100	190	70
8	0	230	70

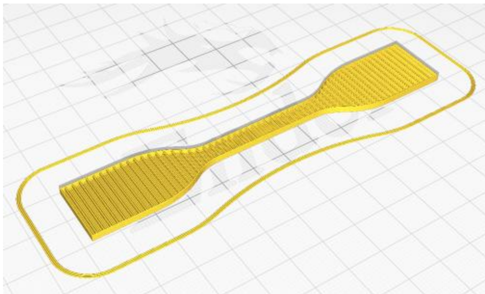


(a)

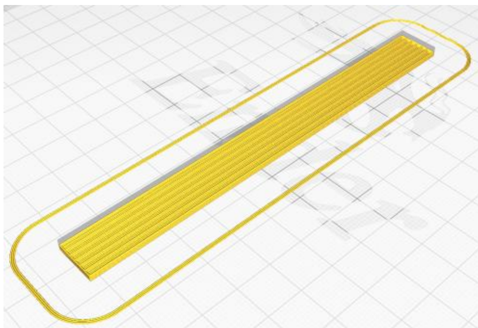


(b)

Figs. 1. (a) Force direction that occurs on ASTM D638 and (b) Force direction that occurs on ASTM D790



(a)



(b)

Figs. 2. (a) Orientation print of ASTM D638 and (b) Orientation print of ASTM D790

The printer used in this experiment is the Ender 3 Pro.

The printer has been placed in an air-conditioned closed room with an average temperature of 26 °C and an average humidity level of 70%. In addition to the ones listed in Table I, several other parameters have been set through the Ultimaker Cura 4.8.0 software standardized for all the print results seen in Fig. 3.

III. Test and Results

III.1. Print Results

The print results show differences in the surface texture, as shown in Figs. 4. Both on the left side, each sample is printed at 190 °C extrusion temperatures, at a glance have a more delicate texture than the right side printed at 230 °C. However, these effects still need further research. Then the print results have been tested for tensile tests and flexural tests. The tests have been carried out using the Shimadzu Universal Testing Machine, AGS series 50 kN for tensile tests and AGX series 50 kN for the flexural test, at the Sentra Polimer BPPT testing site. Then the data results have been put into a factorial design for the ANOVA test. The tensile and the flexural tests are shown in Tables IV and V.

III.2. ANOVA Test

The tensile and the flexural test results have been put into the ANOVA test in order to determine which parameters are significant. The results can be seen in Table III. From the main effects plot and interaction plot, it has been possible to determine which levels will give better results.

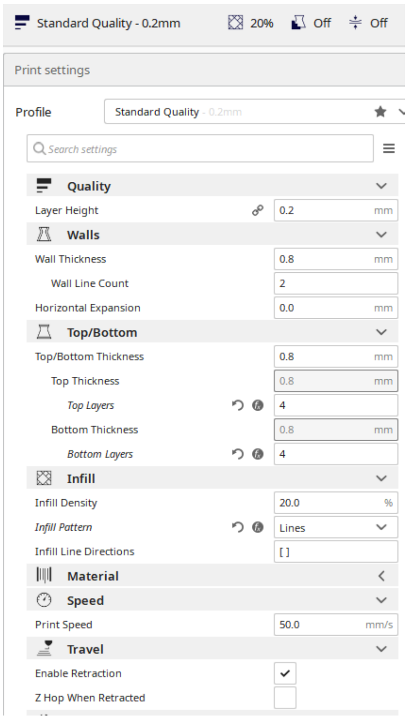
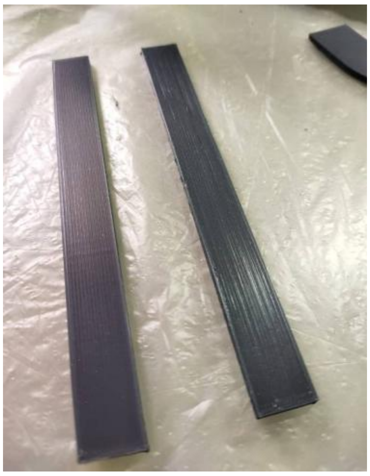


Fig. 3. Parameter in Ultimaker Cura 4.8.0

(a)



(b)

Figs. 4. (a) Print results of ASTM D638 and (b) Print results of ASTM D790

TABLE III
ANOVA TEST CONCLUSION

Significant factor from tensile test	Significant factor from flexural test
• Fan cooling; • Extruder temperature; • Bed temperature; • Interaction of extruder temperature and bed temperature.	• Extruder temperature; • Bed temperature; • Interaction of fan cooling and the extruder temperature.

From the main effects plot and interaction plot of the tensile test in Figs. 5, the levels that will give results that are more desirable will be obtained. The best parameter combination that gives the best result for the tensile test is as follows:

- Fan cooling 100%;
- Extruder temperature 190 °C;
- Bed Temperature 50 °C.

From the main effects plot and interaction plot of the flexural test in Figs. 6, the best parameter combination that gives the best result for the flexural test is as follows:

- Fan cooling 100%;
- Extruder temperature 190 °C;
- Bed Temperature 70 °C.

TABLE IV
TENSILE TEST RESULTS

No.	Sample Size	Fan Cooling (%)	Extruder Temperature (°C)	Bed Temperature (°C)	Mean Ultimate Tensile Strength (UTS) (MPa)
1	3	0	230	50	18.951
2	3	100	230	70	20.787
3	3	0	190	50	25.635
4	3	100	190	50	25.937
5	3	100	230	50	20.797
6	3	0	190	70	21.426
7	3	100	190	70	23.222
8	3	0	230	70	19.587

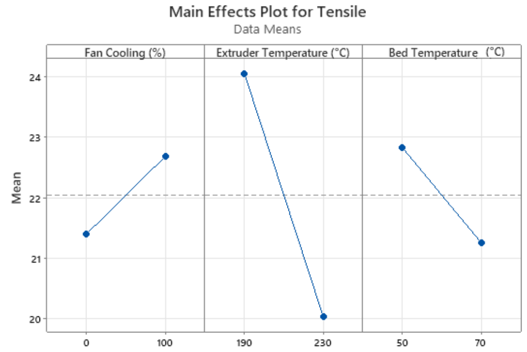
TABLE V
FLEXURAL TEST RESULTS

No.	Sample Size	Fan Cooling (%)	Extruder Temperature (°C)	Bed Temperature (°C)	Mean Ultimate Flexural Strength (UFS) (MPa)
1	5	0	230	50	70.697
2	5	100	230	70	69.684
3	5	0	190	50	72.182
4	5	100	190	50	72.928
5	5	100	230	50	68.461
6	5	0	190	70	72.155
7	5	100	190	70	74.322
8	5	0	230	70	73.685

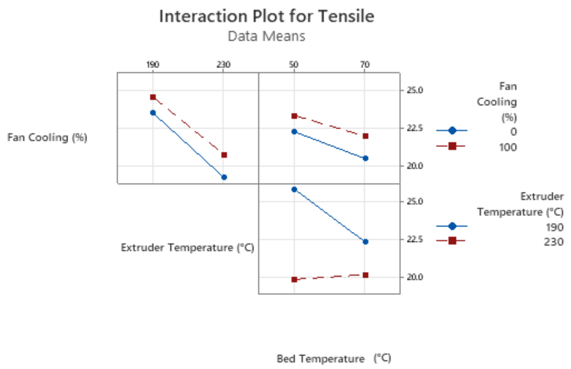
III.3. Pairwise Comparison

The tensile and the flexural test results have given different parameter combinations for each test. Thus, pairwise comparison has been carried out to determine the best factor level by considering the results in the situation when both strengths are needed in a single print.

From Fig. 7, the combination of parameters with the highest tensile strength is No. 4 with an average UTS of 25.937 MPa and No. 3 with an average UTS of 25.635 MPa, which is in-group A.

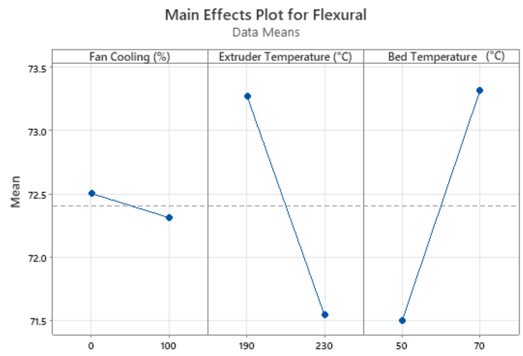


(a)

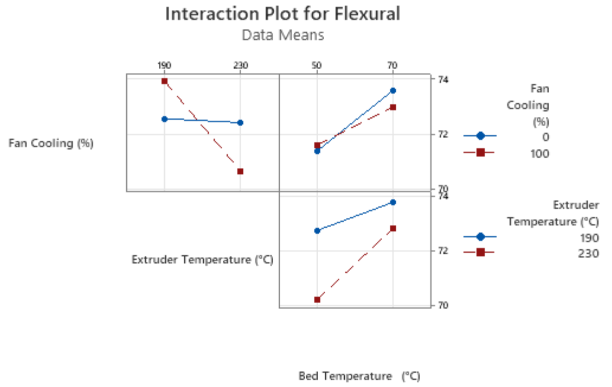


(b)

Figs. 5. (a) Main effects plot and (b) interaction plot of tensile test



(a)



(b)

Figs. 6. (a) Main effects plot and (b) interaction plot of flexural test

Meanwhile, the combination of parameters with the lowest tensile strength is No. 1 with a UTS average of 18.951 MPa, the only combination of parameters not in group C of all the factor combinations in group D.

From Fig. 8, the combination of parameters with the highest flexural strength is No. 7 with a UFS average of 75.117 MPa, No. 8 with a UFS average of 74.028 MPa, No. 4 with a UFS average of 73.486 MPa, No. 6 with an average UFS of 73.103 MPa, and No. 3 with an average UFS of 72.048 which all is in group A.

Grouping Information Using the Fisher LSD Method and 95% Confidence

Variant	N	Mean	Grouping
4 (100, 190, 50)	3	25.937	A
3 (0, 190, 50)	3	25.635	A
7 (100, 190, 70)	3	23.222	B
6 (0, 190, 70)	3	21.43	B C
5 (100, 230, 50)	3	20.797	C D
2 (100, 230, 70)	3	20.787	C D
8 (0, 230, 70)	3	19.587	C D
1 (0, 230, 50)	3	18.951	D

Means that do not share a letter are significantly different.

Fig. 7. Fisher pairwise comparison tensile test

Grouping Information Using the Fisher LSD Method and 95% Confidence

Variant	N	Mean	Grouping
7 (100, 190, 70)	5	74.47	A
8 (0, 230, 70)	5	74.141	A
4 (100, 190, 50)	5	73.464	A B
6 (0, 190, 70)	5	73.103	A B C
3 (0, 190, 50)	5	72.048	A B C D
2 (100, 230, 70)	5	71.55	B C D
1 (0, 230, 50)	5	70.718	C D
5 (100, 230, 50)	5	69.761	D

Means that do not share a letter are significantly different.

Fig. 8. Fisher pairwise comparison flexural test

As for the combination of parameters with the lowest flexural strength is No. 5 with an average UFS of 69.725 MPa, the only factor combination not in group C of all the factor combinations in group D. From the two results of fisher pairwise comparison, only parameter combinations No. 4 and No. 3 are in group A, but No. 4 still has a higher average UTS and UFS than No. 3.

Therefore, parameter combination No. 4, namely with 100% fan cooling, extruder temperature 190 °C, and bed temperature 50 °C, will give the best results when the tensile and the flexural strengths are factored. No. 7 will still give the best results if only the flexural strength alone is considered. In short, the experiment results give the combination of parameters for achieving the most optimal 3D print results in Table VI.

Referring back to Fig. 7, it can be seen that the comparison of the average combination of parameters No. 4 is at 25.937 MPa; the difference is up to 37% higher than the parameter combination No. 1 in 18.951 MPa for its tensile strength.

Meanwhile, on the flexural results, by referring to Fig. 8, it can be seen that the comparison of the average combination of parameter No. 4 is at 73.464 MPa; the difference is 5.3% higher than the parameter combination No. 5 at 69.761 MPa for flexural strength. If Fig. 8 is further seen, for a comparison of the average combination of parameters No. 4, the difference is only 1.4% lower than the parameter combination No. 7, which has the highest average yield for flexural strength, which is 74.47 MPa.

TABLE VI
OPTIMAL COMBINATION OF PARAMETERS FOR EACH CASE

Factor	Tensile and flexural strength	Tensile strength only	Flexural strength only
Fan Cooling (%)	100% (5 m/s)	100% (5 m/s)	100% (5 m/s)
Extruder Temperature (°C)	190	190	190
Bed Temperature (°C)	50	50	70

IV. Discussion

The experiments and the analyses obtained show opposite results to the ones obtained by previous findings as discovered by Lee and Liu [27] and others in the introduction, in which there is an increase in tensile strength when the fan speed is lower and with increasing extrusion temperature and bed temperature, there is an increase in tensile and flexural strengths as well.

However, as mentioned, this is in contrast to this experiment. For better understanding, Table VII and Table VIII should be seen. This anomaly could be due to the characteristics of the PLA recycle itself, where the crystallization temperature occurs at a lower temperature than that of PLA non-recycle, whose results can be seen in Table IX as discovered by Fernandes [30]. However, without crystallization analysis, it cannot be told for sure how this anomaly occurred. As such could be an interesting subject for further research.

TABLE VII
COMPARISON PRINT METHODS FROM TENSILE TEST

Factor	PLA recycle	PLA non-recycle
Fan Cooling (%)	100%	0%
Extruder Temperature (°C)	190	230
Bed Temperature (°C)	50	105

TABLE VIII
COMPARISON PRINT METHODS FROM FLEXURAL TEST

Factor	PLA recycle	PLA non-recycle
Fan Cooling (%)	100%	0%
Extruder Temperature (°C)	190	230
Bed Temperature (°C)	70	105

TABLE IX
RECYCLING EFFECTS ON PLA THERMAL PROPERTIES

Property	PLA non-recycle	After recycling once	After recycling twice
Glass Transition Temperature (°C)	59.86	59.67	59.11
Crystallization Temperature (°C)	123.69	104.34	98.32
Melting Temperature (°C)	165.64	168.39	167.55

V. Conclusion

The aim of this study has been achieved through ANOVA analysis. It can be concluded that the faster cooling, lower bed temperature, and lower extruder temperature for PLA recycle would result in better tensile strength and flexural strength as high as 37% and 5.3%, respectively. However, as stated in the discussion section above, the results have been opposite to the previous study on PLA non-recycle, indicating different optimal parameters for PLA non-recycle and PLA recycle. Because of this, a study on recycled filament performance might need to be revisited to consider the difference between non-recycled filaments and recycle filament's optimal parameters. Furthermore, based on this study, authors also believe the need to investigating other recycle filaments type behavior and optimal parameters before assessing their performance for future study.

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