PLC/PLA/N-HA COMPOSITE SCAFFOLD WITH DIFFERENT POROSITY PERFORMANCE VIA FINITE ELEMENT ANALYSIS SIMULATION

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ABSTRACT

Fused Deposition Modelling (FDM) is a widely used printing process in low-cost additive manufacturing technology. FDM is a well-known method of 3D printing on plastics, however, now it can be used for printing on metallic materials as well. For the past few decades, the polymer material is one of the most preferred choices of material studied for 3D printing especially to produce implants. In this study, nano-Hydroxyaptite incorporated with Polycaprolactone and Polylactic Acid (PCL/PLA/n-HA) are designed to inform of a scaffold with different porosity and compression performance were tested using ANSYS simulation. Combining n-HA into a PCL / PLA composite offers alternative options for the FDM raw material filament formula for a biomedical scaffold. For scaffold design, the dimensions are 10 mm x 10 mm x 10 mm in size. The porosity of the scaffold is set at 35.3%, 47.06%, and 70.59%, which are necessary to study the porosity value of the scaffold that performs under the compression mode. Next, the scaffold was tested via simulation by using Finite Element Analysis in SolidWorks 2020. The mechanical properties analyzed through compression in SolidWorks 2020 is Von Mises Stress, Equivalent Strain, and Resultant Force and the compression value are set at 20N, 30N, 40N, 50N, and 60N respectively. Throughout the analysis, PNC 2 with a porosity of 47.06% resulted in the lowest minimum stress and intermediate value in maximum stress in Von Mises. An equivalent strain through this analysis showed that PNC 2 with a porosity of 47.06% has the ideal characteristics where it has the highest minimum stress and the intermediate maximum strain. In resultant displacement, PNC 3 with 70.59% porosity resulted in the highest value in resultant displacement and it is not an ideal characteristic for a scaffold design in bone regeneration. Overall, PNC 2 with a porosity of 47.06% has shown the most ideal characteristics in Von Mises, Equivalent Strain, and Resultant Displacement and is ideal for scaffold fabrication using PCL/PLA/n-HA composite through 3D printing.

Keywords: three-dimensional (3D) modelling, scaffold, finite element analysis, compression, PCL, HA.

1. INTRODUCTION

Additive manufacturing or 3D printing is a brand-new technique for growing a bodily item from a third-dimensional virtual version through the use of a printer, normally through laying down numerous successive skinny layers of material. Imagine a virtual object, which is a computer drawing, adding material layer by layer to its physical form. There are different types of 3D printing. With the ability to design and manufacture complex designs, 3D printing has rapidly expanded to the medical and pharmaceutical fields. Today, additive manufacturing technology is widely used and rapidly expanded in the field of healthcare. 3D printing will change the healthcare system [1] and 3D printing also include tissue and organ manufacturing, custom prostheses, anatomical models, implants, and drug research [2].

The use of three-dimensional biomedical equipment is the repair of three dimensional anatomical defects and the reconstruction of complex organs with complex three-dimensional microstructures and scaffolds for stem cell differentiation. Various methods based on the principles of tissue engineering have been studied for the regeneration of other functional tissues related to maxillofacial tissue regeneration. Tissue engineering requires scaffolds to provide structure for cell infiltration and proliferation, provide space for the production and remodelling of extracellular matrix, biochemical signals that control cell behavior, and physical connections between damaged tissues.

Fused Deposition Modelling (FDM) is a printing process widely used in low-cost additive manufacturing technology. Fused deposition modelling commonly used a polymer, when Poly-Lactic Acid (PLA) when used as a human implant, it breaks down and produces acidic foods, which can cause undesirable inflammation. Hydroxyapatite (HA) is a taking place mineral shape of calcium phosphate this is well suited to the contents of human bones. Combining n-HA into a PCL / PLA composite, it offers alternative options for the FDM raw material filament formula for biomedical scaffolding where it has potential for future commercialization [3].

A polymer commonly used in fused deposition modelling, Poly-Lactic Acid (PLA), when used as a body implant, degrades and produces acidic products that can cause undesirable inflammation. Hydroxyapatite (HA) is a type of calcium phosphate, which is related to the characteristics of human bones. The addition of n-HA to PCL/PLA compounds provides an alternative to the manufacture of filaments for biomedical stents from FDM raw materials, which has the potential for future commercialization. Scaffold production using FDM is much faster easy and more convenient compared to conventional methods, as well as the mixture of n-HA to PCL/PLA is able to increase the mechanical properties of

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the scaffold design the tissue generation in human bone [4]. For scaffold design, the dimensions are 10 mm x 10 mm x 10 mm. The porosity of the scaffold is set to 35.3%, 47.06%, and 70.59%, which are necessary in order to study the porosity value of the scaffold that is most suitable for commercial use [5].

The aim of this project is to design and stimulates the scaffold with a dimension of 10 mm x 10 mm x 10 mm with different percentage of porosity of 35.3%, 47.06%, and 70.59% with the mixture composition of PCL/PLA/n-HA (15%). The mechanical properties of the scaffold were investigated using Finite Element Analysis in SolidWorks 2020 through compression. The influence of porosity on the mechanical properties of PCL/PLA/n-HA (15%) were analyzed. The compression value for the compression test through the analysis was set to 20N, 30N, 40N, 50N, and 60N. Von Mises Stress, Equivalent Strain, and Resultant Displacement were gained through the analysis.

2. MATERIAL AND METHODS

2.1 Materials

The type of material used in the mixture is PCL/PLA/n-HA. PCL is one of the most widely studied synthetic polymers for tissue engineering. PCL has been useful in the creation of tissue structures for bone formation. Polylactic acid (PLA) is one of the most versatile biopolymers. This material also has good strength, high elastic modulus, good heat sealability, very fast processing, excellent taste, and aroma barrier properties [5]. These PLA materials are compatible, cheap, non-toxic, biocompatible, and easy to use, and are mainly used for FDM [6]. Hydroxyapatite (HA) is the main component of human and animal bones. Due to its chemical properties that mimic the natural bone structure, HA is the most widely used calcium phosphate biomaterial for bone substitutes and bone conduction scaffolds [7]. The formulation of mixture PCL/PLA/n-HA (15%) was mixed using a brabender machine.

Table-1. Blend formulation of PCL/PLA and HA.

Designation	PCL/PLA (wt.%)	HA (wt.%)
MX1	70/30	15

Table-2. Material Properties of PCL/PLA/n-HA [6]

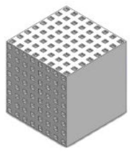
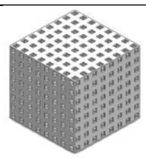
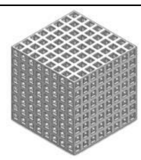
Property	Value
Elastic Modulus (N/mm^2)	57.601
Poisson Ratio (N/mm^2)	0.394
Tensile Strength (N/mm^2)	3.99
Yield Strength (N/mm^2)	56
Shear Modulus (N/mm^2)	4060
Thermal Conductivity (W/m.k)	0.2256

2.2 Characterization of Unit Cell of the Scaffold

Table-3 shows the design of the scaffold with its characteristics. The porosity of the scaffold is calculated using Equation 1:

$$Porosity = (Porous\ Volume / Total\ Volume) \times 100\% \quad (1)$$

Table-3. Characteristics of scaffold design with different value of porosity.

Parameter			
Model Name	PNC 1	PNC 2	PNC 3
Porosity (%)	35.3	47.06	70.59
Total Volume (mm^3)	646.57	529.90	295.49
Surface Area (mm^3)	2495.42	2858.01	2566.08
Mass (g)	0.66	0.54	0.30

2.3 Finite Element Analysis in Solid Works 2020

When performing a simulation experiment, you need to understand exactly the process flow. The Process of Finite Element Analysis in Solid Works 2020 was conducted as the flow in Figure-1. Before running the analysis of the result, all steps shown need to be clearly done or else it affected the result obtained from the analysis.

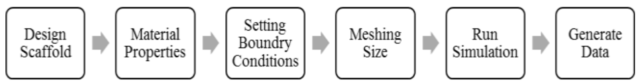


Figure-1. Flow of simulation process in SolidWorks 2020.

3. RESULTS AND DISCUSSIONS

Three scaffolds that were designed with different porosity in the compression simulation were tested. The material properties of PCL/PLA and n-HA were obtained

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from a previous researcher and entered into the custom materials section in the software. In this simulation, the data of Von Mises Stress, Equivalent Strain, and also Resultant Displacement were analysed through the scaffold design in SolidWorks 2020 software.

3.1 Von Mises Stress

Von Mises stress is the amount used to determine whether a given material will deform or collapse. Mainly used for ductile materials such as metals. The von Mises creep criterion stipulates that a material is deformable if its von Mises stress under load is equal to or exceeds the character limit of the same material under a single stress.

Table-4. Result for minimum stress of von mises.

Model Name	**Porosity (%)**	**Minimum Stress ($\times 10^4$) (N/m²)**				
		20N	**30N**	**40N**	**50N**	**60N**
PNC 1	**35.3**	1.867	2.438	3.735	4.668	5.602
PNC 2	**47.06**	1.047	1.861	2.094	2.618	3.141
PNC 3	**70.59**	2.210	3.314	4.419	5.999	7.025

Table-5. Result for maximum stress of von mises.

Model Name	**Porosity (%)**	**Maximum Stress ($\times 10^4$) (N/m²)**				
		20N	**30N**	**40N**	**50N**	**60N**
PNC 1	35.3	144.1	224.6	288.2	360.3	432.3
PNC 2	47.06	152.4	278.1	304.8	381.0	457.2
PNC 3	70.59	259.2	388.9	518.5	757.5	904.1

Based on both graphs of minimum stress and maximum stress of Von Mises, the most significant and ideal scaffold design is PNC 2 with 47.06% of porosity. It is because PNC 2 has the lowest value of minimum stress between PNC 1 and PNC 3 which the value of minimum stress of Von Mises for PNC 2 is 1.047 (N/m²) for 20N, 1.861 (N/m²) for 30N, 2.094 for 40N, 2.618 (N/m²) for 50N and 3.141 (N/m²) for 60N. For the value of maximum stress, PNC 3 represents that scaffold with a porosity of 70.59% has the highest value of maximum stress where it does not have the ideal value of maximum stress. The risk for fracture is less when the value of Von Mises is lower. This is very important because this simulation is about a scaffold that will replace the bone in the human body [8].

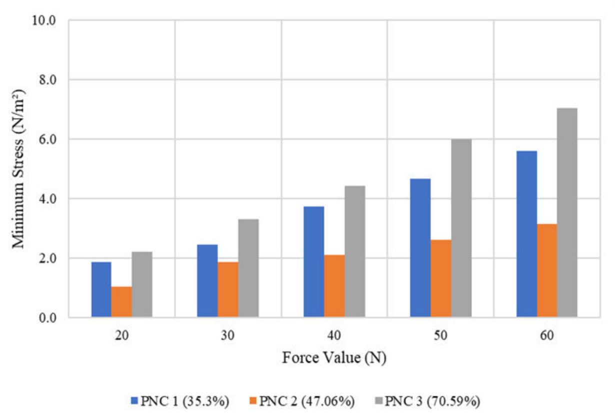

Figure-2. Graph of minimum stress of von mises.

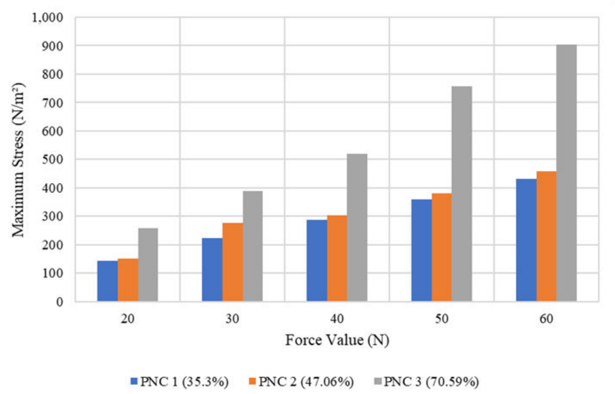

Figure-3. Graph of minimum stress of von mises.

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3.2 Equivalent Strain

Elastic deformation is described because of the restrict of the deformation cost at which an item rebounds and returns to its authentic form after release. An external load beyond the elastic limit results in permanent deformation of the body. For an equivalent strain in this analysis, the data were evaluated with three different scaffolds with different porosity.

Table-6. Result for minimum equivalent strain.

Model Name	Porosity (%)	Minimum Strain ($\times 10^{-4}$) (N/m²)				
		20N	30N	40N	50N	60N
PNC 1	35.3	1.475	2.186	2.949	3.687	4.424
PNC 2	47.06	6.008	9.417	12.020	15.020	18.020
PNC 3	70.59	5.310	7.966	10.620	13.320	15.430

Table-7. Result for maximum equivalent strain.

Model Name	Porosity (%)	Maximum Strain ($\times 10^{-4}$) (N/m²)				
		20N	30N	40N	50N	60N
PNC 1	35.3	198.3	287.4	396.7	495.8	595.0
PNC 2	47.06	201.6	304.8	403.2	503.9	604.7
PNC 3	70.59	348.1	522.2	696.3	952.4	113.3

The graph of minimum and maximum equivalent strain showed all the data that can be analysed to choose the perfect and optimum design of the scaffold. The design of the scaffold that has ideal characteristics is PNC 2 with 47.06% of porosity. To support the statement about the selected design, the data recorded for PNC 2 has the highest minimum value of equivalent strain and intermediate value for the maximum strain, which makes the design of scaffold, PNC 2 the most ideal design between PNC 1 and PNC 3. The risk of scaffold to damage is lower and it is very important in order to make the material a replacement for human bone [9].

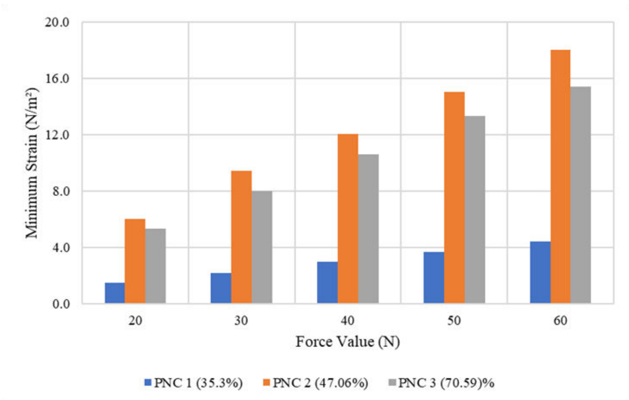

Figure-4. Graph of minimum equivalent strain.

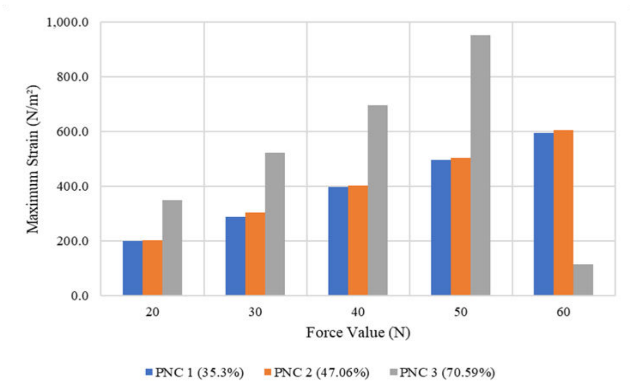

Figure-5. Graph of maximum equivalent strain.

3.3 Resultant Displacement

Resultant Displacement is a change in a location of a point expressed as the distance and direction of the vector measured along a straight line from the initial to the final position.

Table-8. Result for maximum resultant displacement.

Model Name	Porosity (%)	Maximum Strain ($\times 10^{-1}$) (N/mm²)				
		20N	30N	40N	50N	60N
PNC 1	35.3	1.075	1.746	2.150	2.688	3.225
PNC 2	47.06	1.155	1.821	2.310	2.887	3.464
PNC 3	70.59	2.438	3.657	4.876	6.145	7.375

The resultant displacement is where the value of change in the position of a point, expressed as the distance and direction of the vector, is measured along a straight line from the start position to the end position. The risk of high resultant displacement is the design of the scaffold is highly capable to fracture and damage. PNC 3 has the highest value of maximum strain which represents that scaffold with a porosity of 70.59% is not an ideal scaffold. PNC 1 and PNC 2 were the ideal types of scaffold with porosity of 35.3% and 47.06% where the data recorded is only slightly different. As we should know that as the porosity increase, the value of resultant displacement also increases parallel to the porosity on the scaffold design [10].

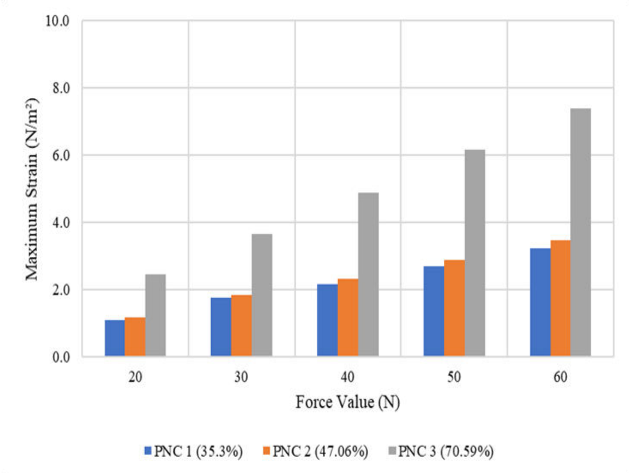

Figure-6. Graph of maximum resultant displacement.

4. CONCLUSIONS

The three parts of mechanical testing have been evaluated through simulations in SolidWorks 2020. For Von Mises Stress, it indicates that PNC 2 with a porosity of 47.06% has the lowest minimum stress and intermediate maximum stress in comparison to PNC 1 and PNC 3. In the simulation to evaluate the Equivalent Strain, PNC 3 with a porosity of 70.59% has the top-notch value of Equivalent Strain which represents that PNC 3 is not an ideal scaffold design correlated to PNC 1 and PNC 2. As the result of Resultant Displacement, the value is approximately the same between PNC 1 and PNC 2, while PNC 3 has the highest value of Resultant Displacement. It shows that PNC 3 is not an ideal and practical design for the scaffold in bone regeneration.

A few suggestions can be analysed and evaluated in the future research for a more accurate and detailed result. Scanning Electron Microscopy (SEM) which is able to provide information about the microstructure of the coated surface, the distribution of the photocatalyst on the substrate surface, and the homogeneity and morphology of the particles in the coating should be included in the findings. Scanning Electron Microscopy is able to prepare a better understanding of the behavior and the properties of the material composite. The concentration of the nano-size HA needs to be investigated, as to how it can affect the properties of the composite mixture. So that the result of the different compositions able to be compared with the other type of concentration in order to determine the ideal concentration for this mixture. In vitro / in vivo and degradation tests should be performed to assess the biocompatibility and osteoconductivity of the PCL/PLA/n-HA composite mixture to determine the potential of this composite mixture for biomedical purposes.

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