EFFECT OF THREE-DIMENSIONAL ARCHITECTURE ON POROSITY, COMPRESSIVE STRENGTH AND MORPHOLOGY OF THE BONE SCAFFOLD

Wei YZ, Ansari MNM*, Nainar SMM, Begum S

Centre for Advanced Materials, College of Engineering, Universiti Tenaga Nasional, Kajang 43000 Selangor, Malaysia

ABSTRACT

This paper discusses the effect of the three dimensional architecture on the porosity and the mechanical properties such as compressive strength of bone scaffolds which are constructed using polypropylene composite. Different types of pore geometry were designed focusing on the compression strength and stiffness of different types of bone in tissue engineering applications. One of the emerging Rapid Prototyping (RP) techniques such as three-dimensional printing (3DP) process was utilized to fabricate three-dimensional (3D) scaffolds that consists of complex internal architecture with highly porous and interconnected channels. Two sets of scaffolds were designed and each set of scaffolds with four different types of 3D architecture. Polypropylene composite in the form of powder was used to build the scaffolds. Water-based binder was used to bond the polypropylene powder. Post-processing infiltration process was carried out when the scaffolds are prepared. Compression tests were conducted onto the fabricated scaffolds. Scanning Electron Microscopy (SEM) was used to study the fractured surface and pore geometry of the scaffolds. The results showed that different types of pore geometry have different mechanical properties and its porosity varies from 60 to 80%.

1.0 Introduction

In recent years, the usage of bio-scaffold is in demand which serves as a template for tissues regeneration. It functions as a carrier for cells, growth factor and also mimics the architectures and features of human tissue to direct the macroscopic process of tissues formation [1]. Scaffold will undergo bulk degradation once implanted into human body. Therefore, initially the scaffolds should have an appropriate compressive strength to sustain in-vivo to provide a correct stress environment for tissue growth.

Nowadays, the field of tissue engineering is rapidly expanding owing to the application of the principles of both engineering and life sciences for the development of biological substitutes that repair, maintain or develop tissue function [2-3]. This unconventional engineering approach in creating artificial organs and tissues, help the patients healing from the fractured of bone or malfunction of organs by regenerate the damaged tissues. In this approach, it involves the in-vitro seeding of specific human cells onto an extracellular matrix. To assist the cell attachment, adhesion, proliferate and differentiated the cell functions, bone scaffolds have been developed by various kinds of bioactive and biodegradable composite polymer [4 - 5]. This temporary bone scaffold is needed to serve as a template for the implanted cells and a physical channel to help the formation of the new tissues [6]. The complex network-like substance with highly porosity and interconnectivity of scaffold, provide the supports of cell attachment and promotes cell proliferation [3]. Thus, a bioactive, biodegradable and biocompatible
composite scaffold is required to design with desired architecture of interconnectivity and porosity [3, 6].

Recently, there are several rapid prototyping (RP) technologies existing including stereolithography apparatus (SLA), selective laser sintering (SLS), laminated object manufacturing (LOM), fused deposition modeling (FDM) and three-dimensional printing (3DP) process [6, 7]. In the year 1987s, Carl Deckard, a researcher from the University of Texas, came up with a good revolutionary idea. Instead of making a part by cutting away at a larger chunk of material, Deckard imagined the material built up layer by layer. He expected the printing three-dimensional models by using laser light to fuse metallic powder into solid prototypes, one layer at a time. Deckard developed this idea into a technique called Selective Laser Sintering. The history of RP is started as this technique of rapid prototyping has such wide ranging scope and applications [8].

Rapid prototyping can be defined as a technique which fabricates a scale model of a part or assembly using three-dimensional computer aided design (CAD) data. This methodology encompasses the designing of the model using a CAD software which is later transformed into a virtual cross sectional model by creating successive layers until completion. one of the methods of RP, the 3D printing process technique is used to produce 3D porous scaffolds for tissue engineering applications. The 3D printer machine is a desktop machine used for producing prototype layered fabrication process, in which the sliced 2D profile of a computer model is printed on a fresh layer of powder via deposition of a suitable binder. These 2D sliced layers were then built by the printer layer by layer till the final object was physically formed [9].

2.0 Materials and Methods

In order to preserve the activity of the role of cells and regulating cell behavior, the design of scaffold must be fulfill several requirements which includes interconnecting porosity that aids in the supply of nutrients, removal of waste products besides promoting bone growth. The size and orientation of pores and channels (macropores) for tissue ingrowth are crucial on a scale of hundreds of microns, and for pores within the macropores (micropores) on a scale of tens of micrometers. In other words, the pore size has been quoted for bone formation in interconnected channels or called macropores should larger than 100μm and the micropores within the channels should less than 10μm in size in scaffolds.

2.1 Sample preparation

The material used to fabricate the scaffolds was polypropylene (PP) which was used in the form of powder. Water-based binder (H2O binder) was used as liquid that printed by print head onto the thin layer of polypropylene powders. Post-processing processes such as infiltration was essential to increase the mechanical properties of scaffolds. All the scaffolds were infiltrated with a constant volume 2 ml of copolymer solution (75% of poly (l-lactide) acid and 25% polycaprolactone in dichloromethane (CH2Cl2)). The concept generation was made to fabricate a set of bone scaffolds with different types as shown in Table 1. One set of scaffolds was drawn using Pro-E software and the other two sets were rescaled by changing the rescale factor to 1.25 and 1.5 in Magics software.

2.2 3D Printing Processes for Scaffolds

The design of scaffolds were completed using Pro-Engineer a Computer Aided Design (CAD) software, and then all the 3D models needed to be converted into STL formats (.stl file) before proceed to the next stage. Magics is a type of rapid prototyping and manufacturing software that used to open the converted STL file and can be used to repair, fix and modify the drawings again in STL format before starting the fabrication of scaffolds. All STL files required to import to Z-corp 310 machine programs (Z print 7.0 software programs). Before the fabrication process, this Z-corp software program was used to preview the 3D model before printing the scaffolds. Besides this, it also used to control the 3D data. For example, variation of layer thickness (usually 0.8 mm to 1 mm) which controls the number of layers that are required to complete the printing process, the position of the parts are controlled by adjusting the top, right and isometric view and the estimated machining time to complete the printing process are calculated using the software. Location of the parts or controlling the position of the parts is important because the overall fabrication time is dependent on the placement of parts in build box space. Also, the orientation of the parts can influence the quality of the surface finish.

2.3 Mechanical properties

Before implementing the compression test, the sample of scaffolds was left to evaporate and dry at room temperature (27 °C) or put into microwave oven for drying about room temperature to ensure that infiltration process is completed. Compression test was performed according to ASTM-D 695 standard using universal testing machine (UTM) INSTRON (Model No.8801). Initial height and diameter of the scaffold were measured using a micrometer. The infiltrated scaffolds were tested with constant speed, 1.0 mm/s. Two sets of specimens were tested: diameter of scaffold, Ø25.0 mm and Ø30.0 mm. In each set, there were four types of scaffold designed with different pore geometry as shown in Table 1.
Table 1 3D Architecture of the Bone Scaffold Design

<table>
<thead>
<tr>
<th>Unit cell geometry</th>
<th>Top-view</th>
<th>Side-View</th>
<th>Description of Lay-down pattern</th>
<th>Pro-E model Isometric view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td></td>
<td></td>
<td>$0^\circ/90^\circ$</td>
<td></td>
</tr>
<tr>
<td>Type 2</td>
<td></td>
<td></td>
<td>$0^\circ/90^\circ$, 3rd layer is located in the middle from 1st layer</td>
<td></td>
</tr>
<tr>
<td>Type 3</td>
<td></td>
<td></td>
<td>$0^\circ/45^\circ/90^\circ$</td>
<td></td>
</tr>
<tr>
<td>Type 4</td>
<td></td>
<td></td>
<td>$0^\circ/45^\circ/60^\circ/90^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Scanning Electron Microscopy (SEM)

Microstructural morphology and particle size analysis of the materials and the scaffolds were conducted using an SEM (S-3400N). The infiltrated scaffolds before and after the compression test were examined under high vacuum conditions at 10.0 kV.

3.0 Results

3.1 Mechanical properties of scaffolds with different 3D architecture

Mechanical properties of the scaffold, such as compression strength, were evaluated from the results of compression tests. From the results obtained, we observe that the scaffolds showed varying degrees of compressive strength with varying porosity as shown in Figure 1 and 2. Higher porosities of scaffolds will lower the compressive strength and stiffness. From Figure 1, we observe that for scaffold of 30.0 mm diameter, the results showed that Type 2 scaffold has the highest compressive strength (i.e. 40.123 MPa) among the others, followed by Type 3 (24.480 MPa) and Type 1 (21.708 MPa). It was also noticed that the Type 4 scaffold has the lowest compressive strength (i.e.19.089 MPa). For the yield strength or yield point of the scaffolds, Type 2 (20.443 MPa) showed the largest yield strength among the others type, followed by Type 3 (19.228 MPa) and Type 1 (11.072 MPa), the lower yield strength value of scaffold is Type 4 (9.829 MPa). The maximum load that it can with stand is shown in Table 2.

Table 2 Compression strength for scaffold (Diameter Ø30 mm)

<table>
<thead>
<tr>
<th>Test No</th>
<th>Max.Load (kN)</th>
<th>Compression Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.345</td>
<td>21.708</td>
</tr>
<tr>
<td>2</td>
<td>28.361</td>
<td>40.123</td>
</tr>
<tr>
<td>3</td>
<td>17.310</td>
<td>24.480</td>
</tr>
<tr>
<td>4</td>
<td>13.493</td>
<td>19.089</td>
</tr>
</tbody>
</table>
Most of the values obtained from the compression tests for the scaffolds of Ø25.0 mm and Ø30.0 mm are recorded in Table 2 and 3 respectively. From Figure 2, we observe that for scaffold Ø25.0 mm, the results that had obtained showed that scaffold Type 2 has the highest compressive strength among the others (i.e. 29.146 MPa), followed by Type 1 (i.e. 21.768 MPa), Type 3 (i.e. 8.278 MPa), and Type 4 (i.e. 6.022 MPa). The design geometry with Type 2 scaffold has better compressive strength while Type 4 has the lowest compressive strength in both the experiments. For the yield strength or yield point of the scaffolds, it was found that Type 2 showed the largest yield strength among the others type (i.e 14.719 MPa). The average value of compressive strength for both set of scaffolds showed that scaffold Type 2 has the highest compressive strength among the others. The maximum load that it can withstand is shown in Table 3. If compare to the mechanical properties of human cortical bone and cancellous bone (refer to Table 4), the compressive strength of Type 2 (Diameter Ø30.0 mm) scaffold (40.123 MPa) is less than cortical bone (130-180 MPa) but larger than cancellous bone (4-12 MPa). It was observed that the Type 2 scaffold has much lower value of stiffness (i.e. 0.198 GPa) when compared with the stiffness of human cortical bone which is around 12 – 18 GPa. Whereas, the stiffness of Type 2 scaffold is in the range of the stiffness value of cancellous bone (i.e. 0.1-0.5 GPa).
Table 4 Mechanical properties and porosity of human bone [10].

<table>
<thead>
<tr>
<th>Type of Bone</th>
<th>Compression Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus (GPa)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>130-180</td>
<td>135-193</td>
<td>50-151</td>
<td>12-18</td>
<td>5-13</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>4-12</td>
<td>NA</td>
<td>1-5</td>
<td>0.1-0.5</td>
<td>30-90</td>
</tr>
</tbody>
</table>

3.2 Scanning Electron Microscopy (SEM)

Figure 3(a) and 3(b) showed SEM images for scaffold diameter 25.0 mm before and after compression test respectively. It has a designed macropore diameter with 712.5 μm before infiltration process. From the SEM images, the scaffold is demonstrated as the macroporous structure showing interconnected pore channels, with macropores size about 643 μm and interconnected micropores size varying from 2 to 9 μm from microporous surface that was formed after infiltration process. The SEM images showed that after infiltration post-processing process, the scaffolds showed some amount of shrinkage. This is because the slightly acidic copolymer solution which contains 75% of poly (l-lactide) acid and 25% polycaprolactone in dichloromethane (CH₂Cl₂) made some effects such as shrinkage. All the compressed scaffolds had displayed cracking and collapse of the scaffold cross-section and its internal microstructures as shown in Figure 3(b). After compression test was performed, more coarse and uneven structure was observed on the scaffold. The pore size of the scaffold and the rough surface finish of the fractured scaffold were also observed.

Figure 3(a) shows the SEM image of the scaffold (Ø 25.0 mm) which is uniformly infiltrated using 25X magnifications. More porous surface is created after infiltration. Shrinkage effect were also exists after infiltration. Figure 3(b) shows the SEM image of the microstructure of scaffold (Ø 25.0 mm) after the compression test.

Discussion and Conclusions

It is concluded that the Type 2 scaffolds irrespective of the diameter have the best pore geometry that has significantly increased the compressive strength of the scaffolds. In addition, Type 2 scaffolds can withstand higher compressive strength with an average porosity of 69%, which is considered as high porosity for scaffolds that favours cell multiplication and proliferation. Although Type 4 scaffolds have the highest porosity among the four types of scaffold design, it could not sustain higher compressive strength. Hence, Type 2 scaffolds are preferred over Type 4 scaffolds.

Acknowledgment

Authors would like to acknowledge the UNITEN Research Grant No. J 510050374 and FYP grant from Universiti Tenaga Nasional. Authors would like to thank M/s. IME Technology for providing Rapid Prototyping facilities and M/s. Quasi-S Sdn.Bhd. Bangi, Selangor for providing SEM laboratory facilities for completing this work.


References


