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BONE SCAFFOLD GEOMETRICAL DESIGN AND MATERIAL SELECTION BY USING ANALYTICAL HIERARCHY PROCESS FOR ADDITIVE MANUFACTURING PROCESS

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Abstract

Bone scaffold is used to aid the regenerative of human organ tissues that caused by a bone fracture. Bone fracture is normally caused by the exertion of exceeding force to the bone that could not be borne or due to bone disease such as osteoporosis. Hence, the use of bone scaffold is needed to provide comfort to a patient and to slowly replace the metal plate for bone implants. Since there is demand in the market for an effective bone scaffold design, the objective of this research is to study the application of Additive Manufacturing (AM) and bone scaffold design in medical application as well as to compare the effectiveness of several materials for its application. Four design of bone scaffolds had been proposed and simulated for compression test and torsional test. A CAD software was used to design bone geometrical structure. In order to select the best bone scaffold design, Analytical Hierarchy Process (AHP) was used as the method to assist in the selection process. Based on the comparative analysis of different design, it was found that Design 1 was the best design. This was mainly due to its geometrical feature that permits higher strength compared to the other geometrical structure of the design. Furthermore, this research compares three different types of materials, namely Alumina Bio-ceramic, Bio-active Glasses and Calcium Phosphate Bio-ceramic. The comparative analysis showed that the best material was Alumina Bio-ceramic. This material has the highest strength compared to other materials due to its capability to sustain the force exerted on it and hence fulfil the priority setting of choosing the material with the highest strength as the main criteria. However, this material is the most expensive material compared to other two materials.

keywords: Aditive manufacturing (am), bone scaffold design, material selection, Analytical Hierarchy Process (AHP)

Abstrak

Perancahtulang digunakan untuk membantu penjanaan semula tisu-tisu organ manusia yang disebabkan oleh kepatahan tulang. Kepatahan tulang biasanya disebabkan oleh kepenatan melebihi kuasa ke tulang yang tidak dapat ditanggung atau penyakit tulang seperti osteoporosis. Oleh itu, penggunaan perancah tulang diperlukan untuk memberi keselesaan kepada pesakit dan perlahan-lahan menggantikan plat logam untuk implan tulang. Oleh kerana ada permintaan di pasaran untuk reka bentuk yang berkesan perancah tulang, objektif kajian ini adalah untuk mengkaji penggunaan Additive Pembuatan (AM) dan reka bentuk tangga-tangga tulang dalam aplikasi perubatan dan juga untuk membandingkan keberkesanan beberapa bahan-bahan untuk permohonan . Empat reka bentuk perancah tulang telah dicadangkan dan simulasi untuk ujian mampatan dan ujian kilasan. Perisian CAD digunakan untuk mereka bentuk struktur tulang geometri. Dalam usaha untuk memilih reka bentuk terbaik perancah tulang, Proses Analisis Hierarki (AHP) telah digunakan sebagai kaedah untuk membantu dalam proses pemilihan. Berdasarkan analisis perbandingan, didapati bahawa Design 1 adalah reka bentuk yang terbaik. Ini adalah disebabkan oleh ciri-ciri geometri mereka yang membenarkan kekuatan yang lebih tinggi berbanding dengan struktur geometri yang lain reka bentuk. Tambahan pula, kajian ini membandingkan tiga jenis bahan, iaitu Alumina Bio-seramik, Kaca Bio-aktif dan Kalsium Fosfat Bio-seramik. Analisis perbandingan menunjukkan bahawa bahan terbaik adalah Alumina Bio-seramik. Bahan ini mempunyai kekuatan paling tinggi berbanding dengan bahan-bahan lain kerana keupayaan untuk mengekalkan daya yang dikenakan ke atasnya dan dengan itu memenuhi keutamaan suasana yang kekuatan sebagai tujuan Kedudukan utamanya. Walau bagaimanapun, bahan ini adalah bahan yang paling mahal

Kata kunci: Pembuatan Pantas (AM) , rekabentuk perancah tulang, pemilihan bahan, Proses Analisis Hierarki (AHP)

1.0 INTRODUCTION

Additive manufacturing (AM) is defined by the American Society for Testing and Materials (ASTM) as the process of making objects from 3D model data by joining the materials layer by layer [1]. It is opposed to subtractive manufacturing technologies, such as machining. The medical field already becomes a leader in the use of AM. In the year 2012, medical application accounted for 16.4% of the overall revenue from the AM market [2]. Medical devices such as hearing aids, dental crowns and surgical implants are small in size and hence it is suitable to use AM technology for parts customization. In other word, AM had accelerated the product development, offered design freedom, optimized part structures and allowed for a high degree of functional integration [3].

Bone scaffold, is one of the application in AM that had been introduced to help to regenerate the tissue and bone, including limbs and organs. Bone scaffold is a three dimensional structure composed of polymer fibers. It is inserted and grip with the damaged cells and begins to rebuild the missing bone and tissue through the tiny holes. As the bone and tissue regenerated, the scaffold is absorbed into the body and disappeared completely. The design of the bone scaffold is complex in geometry. Hence, the manufacture of scaffold depends on the AM system used.

Four designs of bone scaffolds had been proposed and simulated for compression test and torsional test. A CAD software was used to design the bone geometrical structure. In order to select the best bone scaffold design, Analytical Hierarchy Process (AHP) was used as the method to assist in the selection process. Based on the comparative analysis, it was found that Design 1 was the best design. This was mainly due to its geometrical feature that permits higher strength compared to the other geometrical structure of the design. Furthermore, this research compares three different types of materials, namely Alumina Bio-ceramic, Bio-active Glasses and Calcium Phosphate Bio-ceramic. AHP was also used to aid the selection process.

2.0 BACKGROUND

According to [4], the basic principle of AM is that the geometry initially is produced using three dimensional 3D Computer Aided Design (CAD) system and fabricated directly from the CAD data without any additional process planning [4].

Bourhis et al. [5] had mentioned that the AM technologies nowadays allow us to fabricate products that is high added value and this process called as "clean" process. This is mainly due to this process only apply the precise amount of stuff [5]. In addition, the energy consumption is also low when compared with the machining procedure. Furthermore, machining process needs to consider few step of manufacturing step to complete the fabrication of a product. In fact, AM is a process which can instantly obtain the functional part from CAD model with only one manufacturing step.

When the AM technology started to commercialize in the market, medical field started to implement this technology into the field. In the medical field, since the technology is digitally driven for 3D CAD, hence Computerized Tomography (CT) is the alternative technology that developed alongside 3D representation techniques.CT is that a model is directly generated from the machine and combined into a 3D image. This technology also can be used to create the soft tissue images. Besides that, CT technology also is used to create the 3D images for different angle view. Originally, the 3D imaging was just used for imaging and diagnostic purposes, but until now the 3D imaging data can quickly find its way into a CAD / CAM system.

UAR [6] had explained that the bone scaffold as the lightweight materials that can be inserted to the human's body and help to rebuild the broken bones [6]. The process of the absorption of the bone scaffold to replace the injured bone takes around 28 days. The process started with the insertion of the particular shape of the scaffold into the bone fracture parts. The design of the bone scaffold is better if it fits with the injured part.

According to [7], bone scaffold is used for repairing and regeneration of damaged or diseased bone which made of porous degradable materials. The porous bone scaffold allows the material to flow through it and it enables the stem cells from the patient's bone marrow. The bone scaffold slowly absorbed by the bone and recovers the injured bone part. These materials will provide mechanical support to the bone and help to rebuild the bone structure. This is a notable breakthrough of application of AM in medical field and is believed that it can help a lot of patients that suffer with from bone injury.

It is clear that implant in the medical field is important in this modern era. Human is mostly depending on the artificial material insertion if they have any serious body problem. Besides that, organ, sensory and cosmetic implants have also been used in medical field. Currently, the traditional implantation is still used to fulfil the patient's needs. As mentioned earlier, medical field accounted a considerable percentage in the application of AM. The reason that AM becoming widely used is due to the capabilities align well with the needs of medical device segment. Advantages of the AM also help a lot of the implementation of AM in the medical field. However, the medical technology also needs to maintain, assist or restore a person's mobility.

In the medical field, the implants that to be inserted into a patient's body is important to design the implant based on the contour of the human body. Customization of implant ensures the patient to more comfortable and stress free experience during recovery process.The patient will feel comfortable and stress less with the implants that insert into the body. Material used also being considered important when designing the implants. Different materials give a different effect on the surface of the body parts. Hence, there is a need to investigate types of suitable material.

Unfortunately, the implants that has been fabricated using AM technology is expensive compared to the manufacturing of implant with conventional methods. With the consideration of cost, there should be some other method to help to reduce the cost of the surgery process so that every patient can afford to adopt AM technology. AM is a good medical technology to help to cure the patient that needs the implantation. The innovation of the implants should consider to help reduce the cost of hospitalized and follow up treatment. One of the method is through the use of different design and materials. Design of the implant need to have the features of accelerating the healing process besides reducing the strain on both health care system and patient.

Multiple functions of the implants are also important in the design stage. However, most medical devices that will fulfill more than one function are required extra assembly work to make the implant well-functioning. Product development and manufacturing process are aimed to reduce the components as few as possible. Lastly, the demand in the field of AM is high in the recent year. Rapid availability is getting important in the innovation of implants to reach patients. The sooner the implants that launched can be used, the better for the patient and advancement in the medical field.

3.0 METHODOLOGY

This research started of with the modelling of the bone scaffold by using a CAD software as shown in Figure 1.

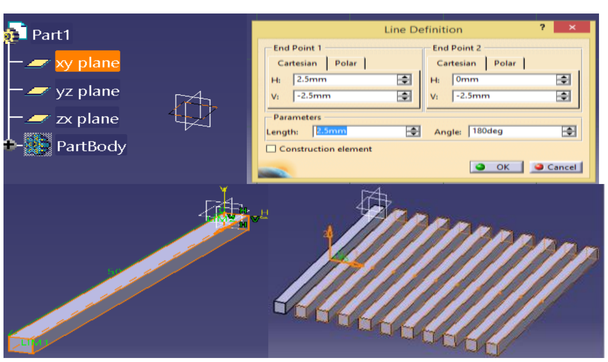


Figure 1 Model of the scaffold part

Simultaneously, the material of the bone scaffold was selected based on the data entered by using Granta: CES Selector Materials Selection Software. A list of 25 different types of materials was listed as the filtration from "bio" search engine and these 25 materials were from a different family of material: ceramics, foam, metals and polymer. With this list, the data were filtered again by only using "ceramic" family's material as the mechanical properties that suitable for the fabrication of bone scaffold and match the mechanical properties with the Bioglass Ceramic (benchmarking material).

Once the design process and the material selection process are completed, all the design will undergo simulation by using ANSYS Simulation software. ANSYS is an engineering simulation software in which enables organizations to predict the exact operation of the product in real life.The following step shows the process of the ANSYS Simulation:

a) Insert the geometry that in the format of "**.stp**".

b) Change the material that defines from the previous process.

c) The geometry has undergone fine "**meshing**" before start to define the static structural parameter that wants to set.

d) Insert the parameter and select the surface that want to apply the parameter and the step followed by evaluating the simulation by clicking "**solution**".

Due to overlap of the result from the simulation of the design with cross with material, Analytical Hierarchy Process (AHP) was used to help in selecting the best scaffold design selection decision. AHP could reduce the complex decisions to a series of pairwise comparisons and followed by synthesizing the results. In this case, the first step is to list out all the factors or criteria for different options. The second step is to specify the hierarchy of decision and followed by establishing the priorities for the option. Then, the pairwise comparison scale between these options was prepared and the synthesizing judgment is made. The following step is to calculate the priority vector for all the factors. Besides that, pairwise matrix between factors and criteria is done and at last, the overall priority ranking was developed. With this ranking, the design or material that with the highest percentage of priority was selected as the best selection. The AHP Analysis was based on the numerical rating as table below:

Table 1 Pairwise Comparison Scale

Verbal Judgement of Preference	Numerical Rating
Extremely preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

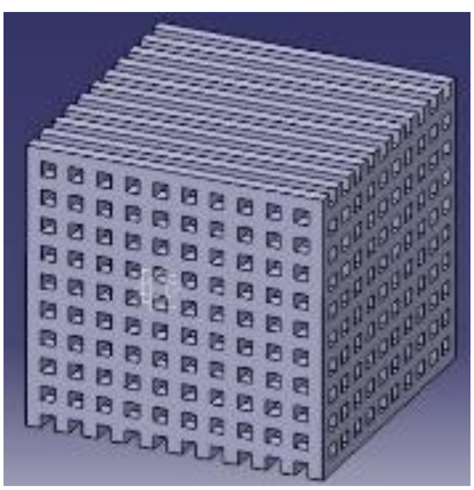
4.0 RESULT AND DISCUSSIONS

4.1 Design of the Bone Scaffolds

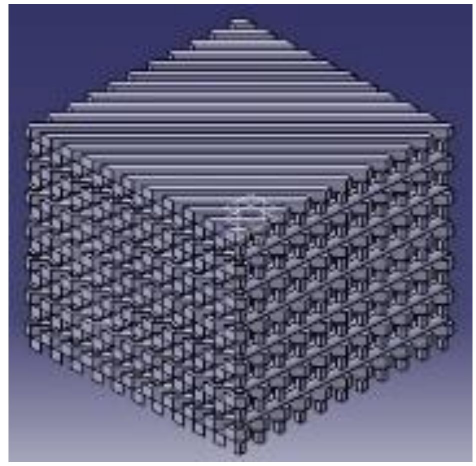
Four designs of the bone scaffold were proposed in this research. One of the common properties of these four designs was the geometry of the design is in cubic and the basic dimension is 50mm x 50mm x 50mm. All the bone scaffold must have porous structures to allow the blood to flow and fasten the recovery period.

Figure 2 shows all the four designs of bone scaffold that developed in isometric view. Design 1 is a simple cubic that build from the small pieces of cubed (parallel) and layering of the orderly arrangement (x axis and y axis arrangement) of it.Design 2 is also simple cubic and the arrangement of cuboid not in parallel order, but in slide 45° with the layering of the rectangular pattern.Design 3 is a cubic with the arrangement in order and packed. Different with Design 1, Design 3 has a solid surface to cover the porous of the design.

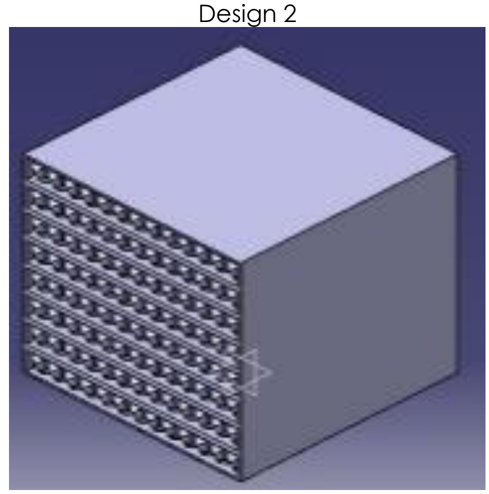
Design 4 is a cubic and the body of the cubic is cut into cylinder part. The body of the cylinder is designed as porous as well.



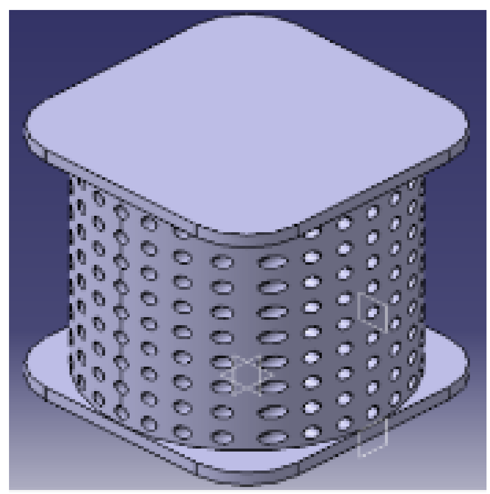
Design 1



Design 2



Design 3



Design 4

Figure 2 Four designs of bone scaffold that developed

4.2 Material Selection

The material that was suitable for the bone scaffold was selected. Bio-active Glasses act as the benchmarking material from the list of material in the CES data. After the lists of 25 materials was filtered out, by studying in detail to understand the properties and the application based on the data given. Out of the 25 materials, there were only two types of materials that suitable in medical implantation and the properties of these materials were close to the properties of the benchmarking material. These two materials are Alumina Bio-ceramic and Calcium Phosphate Bio-ceramic. Table 2 shows the mechanical properties of these three materials:

Table 2 Mechanical properties of three different materials

Properties	Units	ABC	BAG	CPBC
Density	kg/ m^3	3930	3050	3050
Cost	USD/ kg	30.3	20	20
Young Modulus	GPa	380	55	110
Shear Modulus	GPa	156	21	45
Bulk Modulus	GPa	236	55	70
Poisson's Ratio		0.22	0.3	0.23
Tensile Strength	MPa	490	38	90
Compressive Strength	MPa	4400	350	1050

*ABC: Alumina Bio-ceramic; BAG: Bio-active Glasses; CPBC: Calcium Phosphate Bio-ceramic

4.3 ANSYS Simulation

All four designs of the bone scaffold underwent compression and torsion test simulation of the design by using ANSYS Simulation System. In addition, these four designs were also tested with different materials.As mentioned the material used are Alumina Bio-ceramic, Bioglass Bio-ceramic and Calcium Phosphate Bio-ceramic. Hence, there were total 24 simulation results gained from this research.

Figure 3 shows the effect of bone design in total deformation, equivalent stress and normal stress for the compression test. On the other hand, Figure 4 shows the effect of bone design in total deformation, equivalent stress and shear stress in torsion test. In these figure, Design 1 is displayed as this design is easier for reader's to understand. Figure 3 (a) and Figure 4 (a) shows the total deformation of the bone scaffold when the force exerted for 1 second. The diagram shows there has critical part as the edge becoming red and show the part that having the largest deformation of the structure.

For the equivalent stress, the deformation of the bone scaffold will show the torsion direction anticlockwise as shown in the second diagram as in Figure 3 (b) and Figure 4 (b). After 1 second, the bone scaffold for equivalent stress affects the bone scaffold except the edge.

Figure 3 (c) and Figure 4 (c) shows the shear stress of the bone scaffold when the force exerted and it shows that the shear stress did not bring any large effect to the bone scaffold.

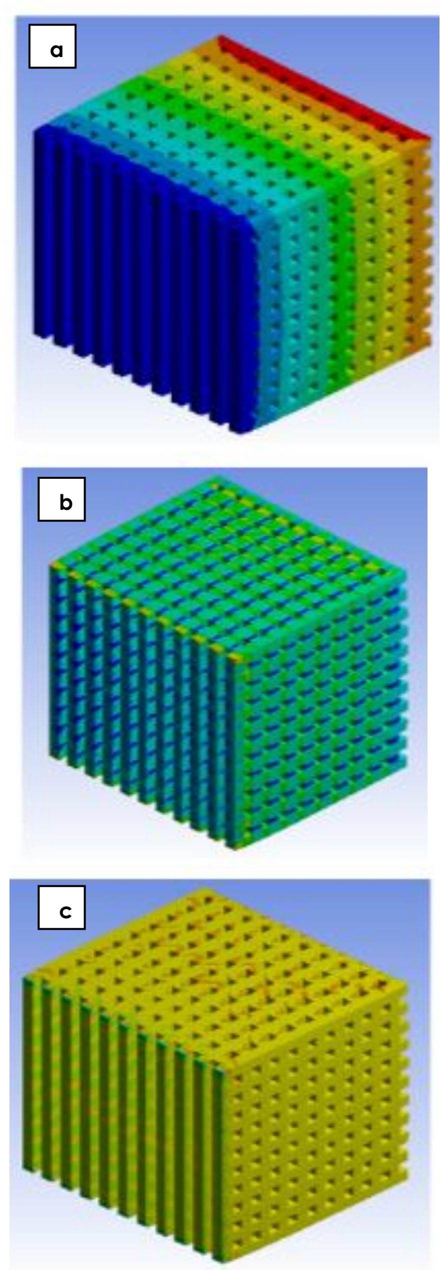


Figure 3 (a), (b) and (c) Effect of bone design in total deformation, equivalent stress and normal stress (Compression test)

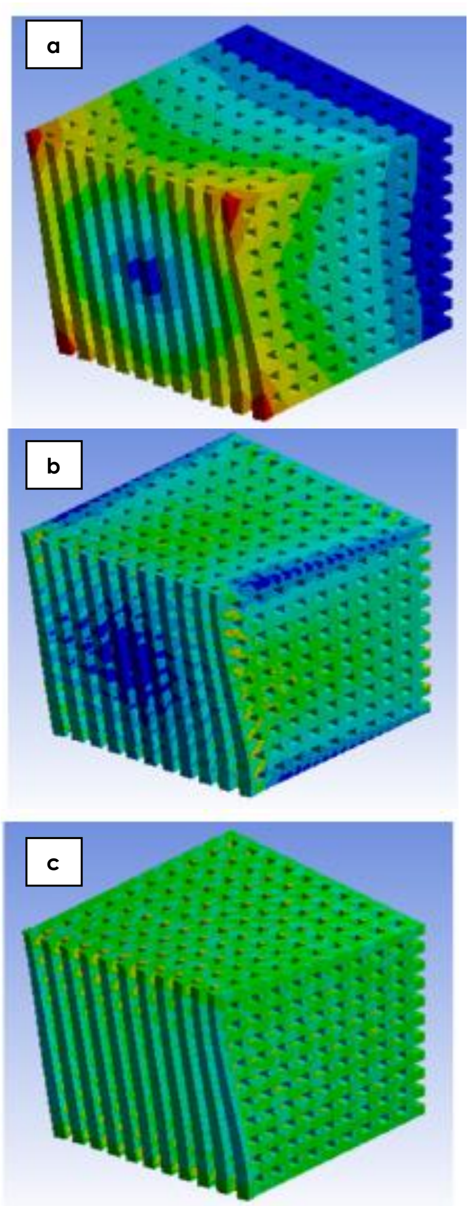


Figure 4 (a), (b) and (c) Effect of bone design in total deformation, equivalent stress and shear stress (Torsion test)

4.4 Analytical Hierarchy Process (AHP) Analysis

4.4.1 Design Selection

There are four factors (clip, cost, strength and pressure) are set to rate the selection process. The design with the highest priority will be chosen as the best design for bone scaffold. Table 3 shows the factors/ criteria for each of the designs which the data obtained from the ANSYS Simulation. Then, followed by establishing priorities for the factors of the design. Table 4, Table 5, Table 6 and Table 7 showed the priorities of the design in term of the factors where the scaling based on the Pairwise Comparison Scale. Finally, Table 8 displayed the priorities of the criterion and last the calculation will show the priority for each design.

Table 3 Factors/ criteria for each of the design

	Design 1	Design 2	Design 3	Design 4
Ease to clip	11 faces	21 faces	1 face	1 face
Cost (USD, $)	6.33	5.69	7.01	7.12
Total Deformation (Compression)	7.423E-08	2.589E-07	1.053E-07	2.420E-07
Equivalent Stress (Compression)	5.200E+05	5.312E+06	9.705E+05	1.761E+06
Total Deformation (Torsion)	2.939E-05	2.255E-04	4.913E-05	1.898E-05
Equivalent Stress (Torsion)	9.137E+07	3.276E+09	1.432E+08	1.283E+08
Shear Stress (Torsion)	2.348E+06	2.024E+07	-4.200E+05	2.470E+07

4.4.2 Establish Priorities

The priorities of the design in term of the criteria is as arrangement below:

a) The priorities of the four criteria in term of the overall goal.

b) The priorities of the four design of bone scaffold in term of the ease of clip.

c) The priorities of the four design of bone scaffold in term of the cost.

d) The priorities of the four design of bone scaffold in term of the strength.

e) The priorities of the four design of bone scaffold in term of the pressure.

Table 4 The priorities of the design in terms of the ease to clip

Ease to clip	Design 1	Design 2	Design 3	Design 4	Priority Vector
Design 1	1	3	0.250	0.250	0.120
Design 2	0.333	1	0.143	0.143	0.052
Design 3	4	7	1	2	0.484
Design 4	4	7	0.5	1	0.344
	9.3	18.0	1.9	3.3	1.000

Table 5 The priorities of the design in terms of the cost

Cost	Design 1	Design 2	Design 3	Design 4	Priority Vector
Design 1	1	0	5	5	0.263
Design 2	4	1	7	7	0.594
Design 3	0.2	0	1	2	0.084
Design 4	0.2	0	0.5	1	0.058
	5.4	1	13.5	15.0	1.000

Table 6 The priorities of the design in terms of the strength

Strength	Design 1	Design 2	Design 3	Design 4	Priority Vector
Design 1	1	7	3	5	0.553
Design 2	0.143	1	0.2	0.25	0.054
Design 3	0.333	5	1	3	0.259
Design 4	0.200	4	0.333	1	0.134
	2	17.0	4.5	9.3	1.000

Table 7 The priorities of the design in terms of the pressure

Pressure	Design 1	Design 2	Design 3	Design 4	Priority Vector
Design 1	1	0.2	0.200	0.200	0.061
Design 2	5	1	0.143	0.143	0.125
Design 3	5	7	1	0.5	0.336
Design 4	5	7	2	1	0.478
	16	15.2	3.3	1.8	1.000

Table 8 Priorities of criterion

Criterion	Ease to clip	Cost	Strength	Pressure	Priority Vector
Ease to clip	1	2	0.25	0.333	0.117
Cost	0.5	1	0.143	0.2	0.063
Strength	4	7	1	3	0.545
Pressure	3	5	0.333	1	0.275
	8.5	15	1.726	4.533	1.000

Calculation for each priority of each design:

1) Design 1:
(0.117*0.120) + (0.063*0.263) + (0.545*0.553) + (0.275*0.061) = 0.348

2) Design 2:
(0.117*0.052) + (0.063*0.594) + (0.545*0.054) + (0.275*0.125) = 0.107

3) Design 3:
(0.117*0.484) + (0.063*0.084) + (0.545*0.259) + (0.275*0.336) = 0.296

4) Design 4:
(0.117*0.344) + (0.063*0.058) + (0.545*0.134) + (0.275*0.478) = 0.249

From the calculation, the highest priority is Design 1 and it indicate that Design 1 is the best design among all design due to it orderly arrangement pattern. The priority, followed by Design 3 and Design 4. Design 2 could be said that not the ideal design for bone scaffold when compared with the other design. The selection was acceptable when the strength of the design was set as the main consideration, followed by pressure, ease to clip and cost.

1) Material Selection
There were three types of materials used to rate for the priority: Alumina Bio-ceramic (ABC), Bio-active Glasses (BAG) and Calcium Phosphate Bio-ceramic (CPBC). In this selection, three factors are set (cost, strength and pressure) to rate and the highest priority of material is chosen as the best material for the bone scaffold.

Table 9 shows the factors/ criteria for each of the materials which the data obtained from the ANSYS Simulation. Then, followed by establishing priorities for the factors of the material. Table 10, Table 11 and Table 12 showed the priorities of the material in term of the factor where the scaling based on the Pairwise Comparison Scale.
Finally, Table 13 displayed the priorities of the criterion and last the calculation will show the priority for each design.

Table 9 Factors/ criteria for each of the material

	ABC	BAG	CPBC
Cost (USD, $)	10.2	7.34	7.34
Total Deformation (Compression)	7.423E-08	2.589E-07	5.111E-07
Equivalent Stress (Compression)	5.200E+05	5.258E+05	5.723E+05
Total Deformation (Torsion)	2.939E-05	1.016E-04	2.040E-04
Equivalent Stress (Torsion)	9.137E+07	9.072E+07	8.271E+07
Shear Stress (Torsion)	2.348E+06	2.365E+06	2.631E+06

Establish priorities

The priorities of the material in term of the criteria is as arrangement below:

a) The priorities of the three criteria in term of the overall goal.

b) The priorities of the three materials of the bone scaffold in term of the cost.

c) The priorities of the three materials of the bone scaffold in term of the strength.

d) The priorities of the three materials of the bone scaffold in term of the pressure.

Table 10 The priorities of the material in terms of the cost

Cost	ABC	BAG	CPBC	Priority Vector
ABC	1	0.25	0.250	0.111
BAG	4	1	1	0.444
CPBC	4	1	1	0.444
	9	2.25	2.25	1.000

Table 11 The priorities of the material in terms of the strength

Strength	ABC	BAG	CPBC	Priority Vector
ABC	1	3	5	0.633
BAG	0.333	1	3	0.260
CPBC	0.2	0.333	1	0.106
	1.5	4.33	9.00	1.000

Table 12 The priorities of the material in terms of the pressure

Pressure	ABC	BAG	CPBC	Priority Vector
ABC	1	2	4	0.557
BAG	0.500	1	3	0.320
CPBC	0.250	0.333	1	0.123
	1.7	3.33	8.00	1.000

Table 13 Priorities of criterion

Criterion	Cost	Strength	Pressure	Priority Vector
Cost	1	0.250	0.250	0.110
Strength	4	1	2	0.544
Pressure	4	0.500	1	0.346
	9.000	1.750	3.250	1.000

Calculation for each priority of each design:

1) Alumina Bio-ceramic:
(0.110*0.111) + (0.544*0.633) + (0.346*0.557)
= 0.549

2) Bio-active Glasses:
(0.110*0.444) + (0.544*0.260) + (0.346*0.320)
= 0.301

3) Calcium Phosphate Bio-ceramic:
(0.110*0.444) + (0.544*0.106) + (0.346*0.123)
= 0.149

From the calculation, the highest priority was ABC and it indicated that ABC was the best material among all material due to higher strength properties. The priority, followed by BAG and last CPBC was not the ideal material for bone scaffold as there had better material compared with this material. This selection is acceptable when the strength of the material as prior consideration, followed by pressure and cost.

4.0 SUMMARY

Bone scaffold is a lightweight bio-materials that is implanted to the human's body and help to rebuild the broken bones. The insertion process starts with the insertion of the scaffold into the bone fracture parts. The blood flows through the bone scaffold and slowly the red blood cell deposited on the surface of the bone scaffold. After a period, the bone scaffold is absorbed by the bone and recover the injured bone part. The design of bone scaffold is complex. This is the reason why AM technology was found suitableto manufacture a bone scaffold.

In this research four bone scaffold geometrical features was designed with a CAD software. After the CAD design was completed, all the design was converted to .stp file and undergoes ANSYS simulation. The study has successfully proposed four designs of bone scaffolds and stimulated it for compression test and torsional test. AHP was used as a method to aid the selection process and it was found that it was useful and provides fast selection decision. Based on the comparative analysis, it was found that Design 1 was the best design. This was mainly due to its geometrical feature (orderly arrangement) that permits higher strength compared to the other geometrical structure of the design.

Furthermore, this research compares three different types of materials, namely Alumina Bio-ceramic, Bio-active Glasses and Calcium Phosphate Bio-ceramic.The comparative analysis shows that the best material is Alumina Bio-ceramic due to its highest strength value.

However, this research proposed that the results obtained as stated above should be validated with the fabrication of the bone scaffold by AM machines such as Electron Beam Modeling and a clinical trial should follow later. However, this process will be time and cost consuming. Only then, if the result from the exact situation is close to the result that obtained from this study, hence the result of the bone scaffold design and the material suggested would then be acceptable.

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