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Research Paper

Design and Fabrication of Bone Scaffold Using Ceramic Composite Filament by 3D Printer

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ABSTRACT

The aging of the middle-aged portion of the population has increased the need for bone tissue scaffolds that help in healing damaged tissue. A 3D printer would be an efficient method for faster and more accurate production of bone scaffolds. This research mainly aims to investigate the pore configuration and the effect of two common ceramic particles (hydroxyapatite (HA) and bioactive glass) on bone scaffold production via fused deposition modeling (FDM). The scaffold building began by determining the optimal scaffold design with respect to percentage porosity and pore shape. The results show that a bone scaffold with square pores and a porosity of 20% is the optimal design. Then, composite filaments made of Polylactic acid (PLA) and the mentioned ceramic particles were prepared. Subsequently, the bone scaffold with a suitable porosity was built using the 3D printer. The results indicated that an appropriate and homogeneous composite with optimal design can constitute a suitable bone scaffold that can benefit from improved biodegradability, adequate mechanical strength, and increased bone regeneration time.

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1. Introduction

The human body consists of a complicated network of organs and tissues performing specific tasks. Aging causes various changes in the body, which result in damage to the tissues or disrupt their performance. A major group of tissues in the body is the bones. The bones are one of the most important components of the human body. Their major characteristics are their crystalline structure, morphology, particle size, and directionality. Moreover, they are a type of porous biocomposite consisting of organic substances, such as collagen, glycoproteins, glycosaminoglycans (GAGs), and inorganic substances, such as hydroxyapatite [1].

Various occurrences, such as war, disease, accidents, and natural disasters, may cause damage to bone tissue. Most bone damage in the bodyself-regeneration with minimum treatment. Nevertheless, self-regeneration may not occur due to fracture malunion, complete bone destruction caused by tumors, and infection, which would require further treatment. These issues highlight the significance of tissue engineering. In tissue engineering, biodegradable scaffolds and bioactive molecules are used together to activate tissue regeneration mechanisms, stimulate self-healing, and accelerate the replacement of the scaffold with regenerated tissue [2]. The key step in tissue engineering is the construction and development of three-dimensional porous scaffolds imitating the extracellular matrix so as to assist cell organization and provide suitable signals for cellular function regulation and adequate mechanical support until the natural extracellular matrix is formed. For better healing properties, a given scaffold must satisfy the following requirements: (1) a pore size between 200 µm and 400 µm, (2) mechanical properties (including compressive strength) similar to those of a bone, and (3) adequate biocompatibility with the body [3]. It must be noted that biodegradable scaffolds can significantly reduce problems occurring after the use of scaffolds.

The pore size of an ideal scaffold must provide space for cell growth inside the scaffold. Most scaffold construction methods suffer from the inability to control the structure, pore grid, and pore size appropriately. To overcome this problem, researchers proposed 3D additive manufacturing (AM) methods for scaffold construction [4-6]. The main objective of the present paper is to determine the best bone scaffold design with respect to pore layout and to compare polymer scaffolds with composite scaffolds constructed using a 3D printer in terms of mechanical strength.

Extensive research has been conducted in this regard, including the work by Lin et al. [7]. They fabricated cylindrical porous scaffolds of 20 mm diameter and 10 mm height made of beta-tricalcium phosphate using selective laser melting. Their results indicated a reduction in compressive strength due to an increase in porosity in the three-dimensional scaffolds. Rohani et al. [8] investigated the effect of shape on ceramic scaffolds. They demonstrated that constructing scaffolds with large interconnected pores and a mechanical strength equivalent to that of cortical bones is a major challenge. Eshraghi et al. [9] experimentally and numerically determined the tensile and compressive mechanical properties of scaffolds made of polycaprolactone with one-, two-, and three-dimensional architecture using selective laser melting. The results showed that the one-dimensional calculated strength of the specimen was larger than the corresponding experimental value. However, a change in geometry from one-dimensional to two-dimensional and three-dimensional resulted in an experimental specimen strength that was larger than the calculated value. Zhang et al. [10] used the composite of PLLA and nano-HA to build bone scaffolds by using FDM. They showed that this composite can satisfy the smoothness of printing. Also in vitro using HA verified the bone osteogenic property. Kim et al. [11] used composite PCL/ HA to fabricate the filament for FDM 3D printer. They showed that different content of HA in filament can change the mechanical and electrical properties of bone scaffolds fabricated by composite filament. Despite numerous studies, an optimal bone scaffold (considering design and material simultaneously) has not been constructed for tissue engineering so far. This paper focused on the optimized composite scaffold for the first time. It is worth noting that none of the materials used in the construction of bone scaffolds satisfies all the needs and requirements alone. Polymers are biodegradable, controllable, and suitable for cell transfer, but they are weak in terms of mechanical properties. On the other hand, ceramics are strong and appropriate for bone generation, but they are vulnerable to fracture. Hence, a composite made of polymers and ceramics used to construct scaffolds can result in faster bone healing. In fact, the use of ceramics alongside polymers to build scaffolds is an optimal solution since natural bone tissue is itself a nano-composite of polymer and ceramic.

Accordingly, the present research attempts first to optimize the scaffold design with respect to strength and subsequently to construct a biodegradable bone scaffold using a 3D printer in order to improve repair speed.

2. Materials and methods

Scaffolds are required to meet the strength demands and stand loads exerted at the implant location. Various factors affect the mechanical properties of scaffolds, the most important of which are the percentage of porosity and the shape and arrangement of pores. Previous research has shown that an increase in porosity reduces the modulus of elasticity and that the pore shape can considerably affect the mechanical properties [12-13].

2.1. Optimized design

Ideally, three-dimensional scaffolds must be designed in such a way that the scaffold must be very porous, consist of interconnected pores, and have a sufficient pore size for the diffusion of cells [14]. Thus, this paper attempts to present a novel structure for scaffold construction via 3D printing and to examine the mechanical properties of this structure with different lay-ups and porosities. The scaffolds were designed as repetitive unit cells in the form of three-dimensional trusses. The scaffold samples were designed in CATIA V2016 with a height of 20 mm, a diameter of 10 mm, and different pore sizes in the unit cell. The design files were converted to the STL format. In this paper, the bone scaffolds were considered in 3 different types in the form of walled squares pore, hexagons, and wall-less squares. The present research used fused deposition modeling by the 3D printer to construct the bone scaffold. First, a polymer filament made of PLA with an average molecular weight of 10000 g/mol was used to construct the scaffolds, as shown in Fig. 1. The SEM image was utilized to display the layers in one of the scaffolds (for example the hexagonal scaffold) in order to ensure correct filament deposition by the 3D printer. As seen in Fig. 2, the polymer filament layers are deposited parallel to each other to construct the scaffold, as expected. At first, the scaffold with the form of a walled square scaffold is examined to check the effect of porosities. In this step, 4 different porosities (20%, 34.5%, 50%, and 60%) are considered for the scaffold, and a compression test is used to compare the mechanical properties. The compression platens were set to a speed of 0.7 mm/s. The specimen was placed in the middle of the machine, and the load is exerted on its surface up to fracture with the stress-strain curve being plotted at every instant.

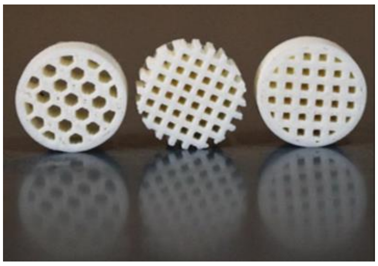


Fig. 1. Constructed the 3 scaffold types using the 3D printer (from left to right: hexagon pore, wall-less square pore and walled square pore).

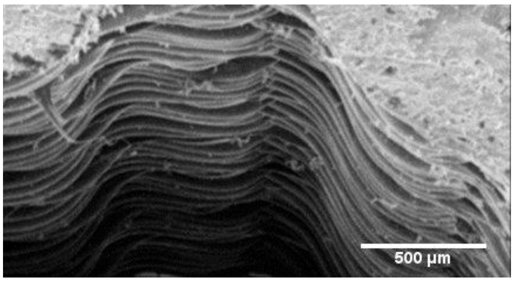


Fig. 2. SEM image of hexagonal scaffold

Fig. 3 displays the changes in stress versus elongation (Elongation is a measure of deformation that occurs before a material eventually breaks when subjected to a tensile load) for 4 of the square scaffolds with different porosities (20%, 34.5%, 50%, and 60%). As seen in the figure, all three graphs contain elastic, plastic, and compressive regions. All the specimens first enter the linear elastic zone and then reach the plastic state. In the plastic zone, the stress becomes constant after some time since the layers are placed on top of one another. This region is caused by the layers bearing external forces. These layers lose their strength suddenly after some time and enter the compressive zone as the external loads increase. In fact, this region is created due to fracture in the porous structure of the scaffold. After this fracture, the study of stress is stopped. The results indicate that the 20% specimen undergoes identical changes at higher stress and, hence, possesses higher strength than the other specimens. As a result, an increase in porosity reduced the strength and the modulus of elasticity (the linear slope of the stress-strain curve).

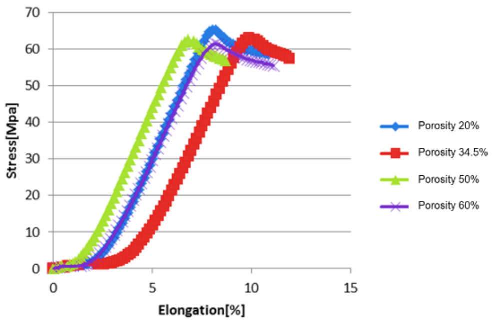


Fig. 3. Graphs of cpmpressive stress versus elongation for different porosities

Subsequently, the porosity was considered constant at 20%, and the impact of the pore shape on the compressive strength was investigated. Table 1 displays the Mean peak stress obtained from the compressive strength tests of three different design shapes (square pore with an external wall, square pore without an external wall, and hexagonal pore as shown in Fig. 1). As the results indicate, the square pores with external walls can withstand the largest stress and possess the highest modulus of elasticity. The wall-less square structure ranks second, followed by the hexagonal structure. It is clear that the pore layout can remarkably affect the strength of the scaffold.

Table 1. Maximum Mean stress for 3 types of pores

Material	Elongation %	Mean stress (MPa)
Scaffold with square pore	9.9	88.2
Scaffold with square pore without wall	8	81.1
Scaffold with hexagonal pore	8.5	63.26

2.2. Effects of materials

After the most suitable scaffold design is determined, the effect of the scaffold material on mechanical strength was investigated by adding the ceramic powder to the polymer filament. In the present work, the polymer-ceramic composite filament (made of PLA+ceramic particles) was considered as the 3D printing material due to properties such as a low softening temperature, biocompatibility, lack of local or systemic toxicity, low price, and good availability compared to other materials. PLA is a common polymer used to fabricate bone scaffolds. This substance is biodegradable is can lead to fast cell growth in the scaffold if combined with ceramic particles.

Moreover, since bones are a compound of natural polymer and bioapatite; therefore, a combination of biodegradable polymer and bioceramic is recommended for constructing bone scaffolds [15]. Composite materials possess the properties of both substances and, thus, are the best option for building scaffolds.

In the present paper, various percentages of bioactive glass (bioglass) (BG) ceramic powder with a density 3.3 g/cm^3 and nano hydroxyl apatite (HA) with a density 2.916 g/cm^3 were examined for preparing the composite filament for 3D printing. It must be noted that the optimal weight percentages for the ceramic powders were determined using the MFI (Melt Flow Index) test. Since adding ceramic powder increases the MFI and reduces the viscosity, specifying the optimal percentage of ceramic powder is of considerable importance. In fact, MFI is the inverse of viscosity. Hence, as the amount of ceramic powder increases, the substance thins and fluidity increases. It must be noted that, in this case, the probability of the substance ejecting faster from the nozzle and the resulting part becoming brittle increases. Accordingly, granule PLA (made by NatureWorks) with 1 wt% of bioglass powder and nano-hydroxyapatite (made by Pardis Pajoohesh Fanavaran Co., Yazd, Iran), separately, were used to construct the composite filament.

First, to determine and compare the tensile strength of the composite for the 3D printing material, the composite sheet was prepared using the P200P hot press machine made by Doctor Clean, Germany. The resulting sheet was cut into dumbbells for the tensile tests of the three specimens (polymer, polymer-bioglass composite, and polymer-hydroxyapatite composite), as shown in Fig. 4.

Fig. 4. The sheet in the form of dumbbells for use in the traction machine

3. Results and discussion

The tensile test was performed for the three specimens using the Instron 4411 device, and the results are displayed in Fig. 5. According to the results, adding ceramic powder somehow reduced the tensile strength. This was due to the addition of a new substance to the base material, which broke the polymer structure. Next, single and twin screw extruders were used to prepare the granule and, thus, the composite filament with a diameter of 1.75 mm. Two prepared composite granules and specimens are shown in Fig. 6. The internal filament was made of polymer and bioactive glass, and the external filament was made of polymer and hydroxyapatite.

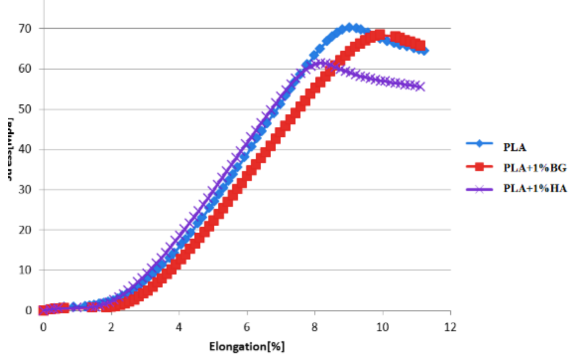
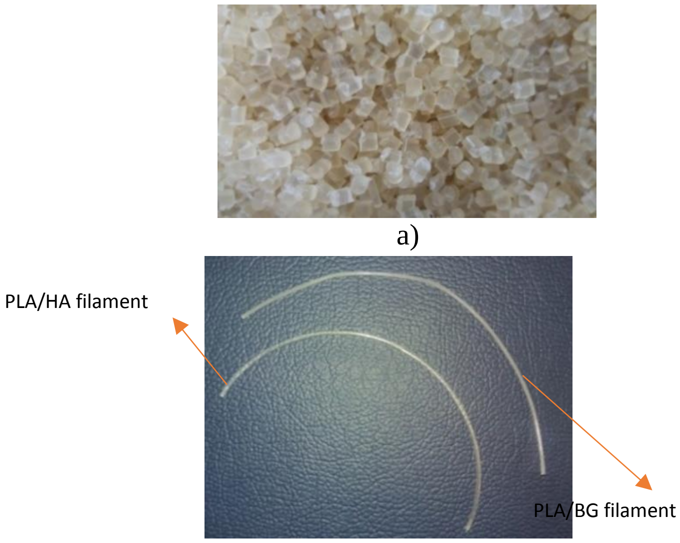


Fig 5. Tensile strength test results of composite filaments



a)

b)

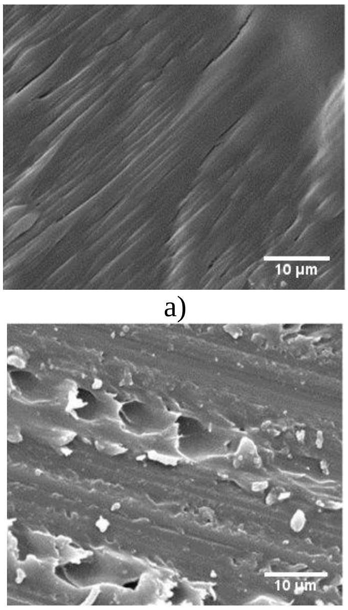
Fig. 6. Composite a) granules b) filaments

Scanning electron microscopy (SEM) analysis was employed to examine the morphology and homogeneity of the composite filament. This analysis is among the most well-known microscopy methods used to produce enlarged images. The results of this analysis are displayed in Fig. 7.

As seen in the figure, the ceramic powder has been scattered well in the bioactive glass composite filament, and good homogeneity is observed throughout the structure. On the other hand, the scattering is not acceptable in the hydroxyapatite composite filament. As a result, the tensile strength of the filament obtained from bioactive glass is better than that of the filament obtained from hydroxyapatite.

Subsequently, three bone scaffolds were fabricated using the polymer and composite filaments (with the optimal design studied in the previous section). It must be noted that the pores were 400 µm in diameter and interconnected, leading to fast cell growth and bone tissue regeneration.

A feature of bone scaffolds is their good mechanical properties, such as compressive strength. For this reason, the compression test was performed on the mentioned three scaffolds, with the results shown in Fig. 8. As seen in the figure, the compressive strength of the polymer scaffold is the highest (4050 N), while that of the hydroxyapatite composite scaffold is the lowest (1750 N). As shown in Fig. 8, a low compressive strength is not unexpected in this scaffold due to the inhomogeneous nature of the prepared filament and the inappropriate scattering of the ceramic powder in the polymer medium. Nonetheless, it is worth mentioning that the maximum compressive strengths of all three specimens are in the range proposed for the bone scaffold. Accordingly, the bioglass power can be added to the PLA granule due to its better compatibility with the bone tissue and its better ability to withstand compressive loads (3000 N). As such, one can improve the bone healing time via the presence of the bioceramic powder while maintaining a good compressive strength in the bone scaffold. In fact, the composite scaffold with bioglass can be used as a regenerative scaffold with excellent mechanical and biological properties in the human body.



a)

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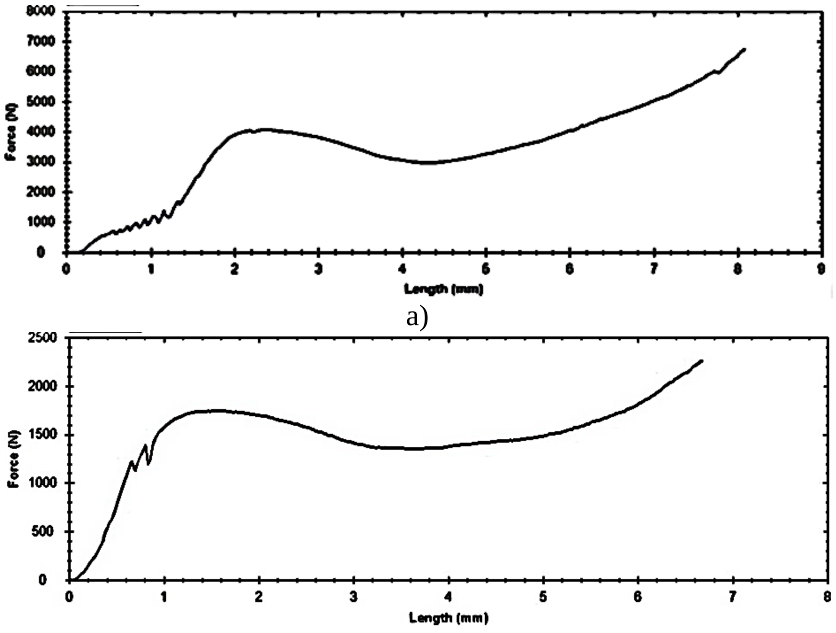
Fig 7. SEM images of composite filaments (a: composite filament of PLA/BG, b: composite filament of PLA/HA)



a)

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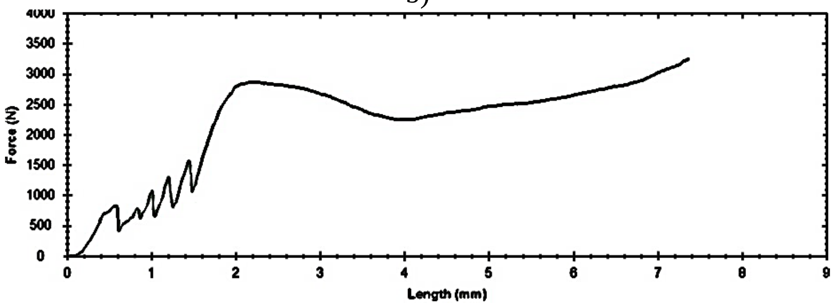

c)

Fig 8. Compressive strength test results in bone scaffold a) PLA b) composite of PLA/HA c) composite of PLA/BG.

4. Conclusions

Among body tissues, the bones possess a high potential for regeneration and, therefore, are a good specimen for regeneration examination. Scaffolds are of utmost significance to bone tissue engineering and act as a temporary medium for cell adhesion. Therefore, constructing optimal scaffolds (in terms of pore layout and scaffold material) that can withstand adequate compressive loads has attracted attention in recent years. In this paper, first, a bone scaffold with square pores was examined by considering different porosities, and a porosity of 20% was selected as the optimal value by conducting compressive tests. Next, three different designs were studied as the proposed pore shapes. The results indicated that the walled square shape was able to stand the highest compressive loads. Subsequently, a bone scaffold with square pores and a porosity of 20% was constructed using various filaments. A 3D printer was employed for this purpose. The results showed that adding bioglass powder to the PLA polymer filament, as opposed to hydroxyapatite powder, can improve healing time given the compatibility of ceramic powders with the bone material despite reducing the compressive strength of the scaffold [16-18]. The hydroxyapatite powder was unable to provide an acceptable compressive strength due to inhomogeneous distribution inside the polymer filament. Therefore, a composite bone scaffold (PLA/bioglass powder) with square and walled pores is proposed to withstand compressive loads.

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