Design, analysis, fabrication and testing of PC porous scaffolds using rapid prototyping in clinical applications

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ABSTRACT

Introduction and Aim: Rapid prototyping is an advanced fabricating method, where three dimensional objects are built precisely from their three-dimensional computer aided design models in a very short duration. In contrast to traditional machining methods, most of the rapid prototyping techniques tend to fabricate parts based on additive manufacturing process. Fabrication of biomaterial into 3-D scaffold structures is the next vital step in the development of bone implants depending on bone injuries of individual patients, and it is highly demanding among the Indian orthopedic surgeons for treating those bone related defects. Therefore, the need for reliable and economically feasible design, better biomaterials, and efficient fabrication method for scaffold to treat musculoskeletal defects has increased in recent years.

Materials and Methods: Investigation of scaffold for porous structured bone implant is a recently emerging field in medicine and is involved in developing artificial bones like structure using materials like Tri Calcium Phosphate (TCP), Polyether ether ketone (PEEK), Hydroxyapatite (HA), Polycaprolactone, polycarbonate (PC), poly (l-lactide) PLLA or Polyamide (PA) etc., by incorporating pores in the scaffold. In this research, the samples of the scaffold specimens were designed and fabricated using Stereo lithography technique with biocompatible PC resin and the strength of each sample were analyzed.

Results: The porous scaffold models are structured with different designs utilizing the CAD software. The porous scaffold with various porosity and pore shape is analyzed through Finite Element Analysis (FEA). StereolithographyViperSi2 method was utilized to manufacture the polycarbonate scaffold. The manufactured rhombus pore model shows the stress value esteems around 200 MPa¸ which is nearest to the compressive strength of human bone. Subsequently the rhombus pore model gives better mechanical load bearing capacity when implanted for tissue recovery in bones.

Conclusion: Bisphenol-A Polycarbonate material give better surface completion, 100% pore interconnectivity and new tissue arrangement of the fabricated porous scaffold. The SLA technique offers the more noteworthy load bearing quality and great exactness of the fabricated scaffold.

Keywords: Rapid prototyping; porous scaffold; bio-compatible; pore size; porosity.

INTRODUCTION

Present additive manufacturing enterprises ceaselessly endeavor to improve the advancement cycles with high caliber and cost-effective items to keep up market aggressiveness. Along these lines, the requirement for Rapid Prototyping Techniques (RPT) has begun to assume significant job in fast item improvement cycle for complex item. Dimensional exactness and surface completion are the strengths of Rapid Prototyping (RP), particularly in the event that they are utilized for shape improvement (1-3). This research work deals with designing, fabrication and testing the load bearing ability of scaffold specimens with different pore geometry and porosity.

MATERIALS AND METHODS

Polycarbonate fills a vital specialty as a standout amongst the most prominent liquid material in the clinical applications (4, 5). Bisphenol-A polycarbonate has been monetarily accessible since the 1970s, and its utilization in medicinal gadgets dates from around that time. Having a wide scope of physical properties polycarbonate offers good load bearing capacity (6-9), unbending nature, and durability that counteracts conceivably hazardous material disappointments (10-12). The biocompatibility is fundamental for any material utilized in immediate or roundabout contact with patients, polycarbonate (PC) grades are accessible that agree to biocompatibility testing benchmarks (13-15).

Design of porous scaffold

The design of porous scaffold model plays an important role in keeping the load bearing of the porous structure. CAD models of porous scaffold designs with different pore geometry and porosities ranges are modeling. The porosity of the structure is modified by differing the spacing between the pores. The scaffold porosity is computed as the proportion of void volume relative to the total volume within the design. The following three different pore configurations were used for this research (11, 16).

Scaffold requirements

The scaffold material is one of the main design factors to be considered in TE of scaffold. The material chosen for the scaffold should meet the following criteria:

- Biocompatibility
- Mechanical strength
- Cell viability
- Pore size
- Porosity

The mechanical properties of the material are especially vital because of the higher load bearing nature of the objective. All the more unequivocally, a porous scaffold material must keep up its basic surface design without surface defects during manufacturing, clinical dealing with, and obsession at the implantation. The implanted material framing new cells from hurtful mechanical forces and withstands the load bearing condition until the new cells can expect the load bearing properties (12, 13).

Types of design and their properties

The porous scaffolds are designed with various configurations using the CAD modeling software. The scaffold with different porosity and pore shape is analyzed through Finite Element Analysis (FEA). All the models were analyzed using the FEA and to identify the best model of hexagonal, cubical and Rhombus with suitable porosity. The scaffold pore size studied is in the range of 400μm to 1905μm and the porosity ranges from 50% to 60% for the purpose of quick new bone tissue formation. The following three porous scaffold models with different cell configurations were selected for fabrication.

- Hexagonal pore model
- Cubical pore model
- Rhombus pore model

Porosity is one of the important properties to be considered while designing a scaffold. In the above-mentioned scaffold models, the porosity ranges from 55% to 60%. The pore size is maintained as 400μm-1905μm for all the three models as shown in Table 1. The porosity and the strength are dependent on the pore size. Hence, appropriate pore size was assigned in order to achieve the expected strength.

Table 1: Porous scaffold details

Scaffold Design	Porosity in %	Pore size in µm
Hexagonal pore model	59.08	1905
Cubical pore model	57.02	1500
Rhombus pore model	55.40	424

CAD Model of porous scaffold

The CAD models of the porous scaffolds were created using the above-mentioned parameters. And these CAD models were converted into STL file and were given as input to the RP machine.

Hexagonal pore model

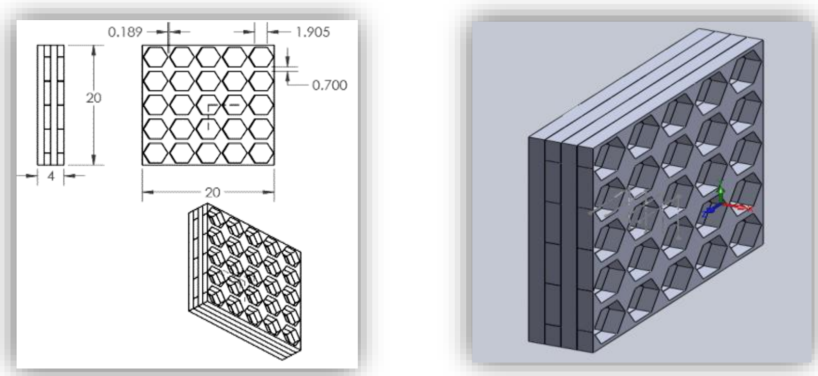

Fig.1: CAD model of Hexagonal pore scaffold

The scaffold was of the size 20x20x4 mm cuboids as shown in Fig. 1. The hexagonal pore size was 1900µm and these pores were interconnected to each other along the row and column. The porosity of the scaffold was identified as 59.08%. The gaps between the pores were provided in order obtain the required porosity. The hexagonal pores were of thickness 1mm. The scaffold was constructed with drifted pores in order to improve the strength of the bone tissues.

Cubical pore model

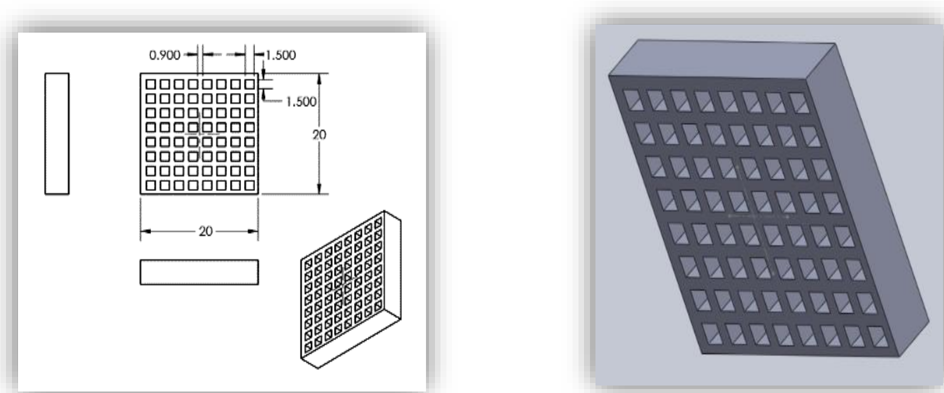

Fig.2: CAD model of cubical pore scaffold

The scaffold was of the size 20x20x4 mm cuboid as shown in Fig. 2. The cubical pore size was 1500 µm and these pores were interconnected to each other along the row and column. The porosity of the scaffold was identified as 57.02%. The gaps between the pores were provided in order obtain the required porosity. The cubical pores were of thickness 4mm.

Rhombus pore model The scaffold was of the size 20x20x4 mm cuboids Fig. 3. The rhombus pore size was 424µm these pores were interconnected to each other along the row and column. The porosity of the scaffold was determined as 55.4%. The gaps between the pores were provided in order obtain the required porosity. The rhombus pores were of thickness 1mm. The scaffold was constructed with drifted pores in order to enhance the strength of the bone tissues.

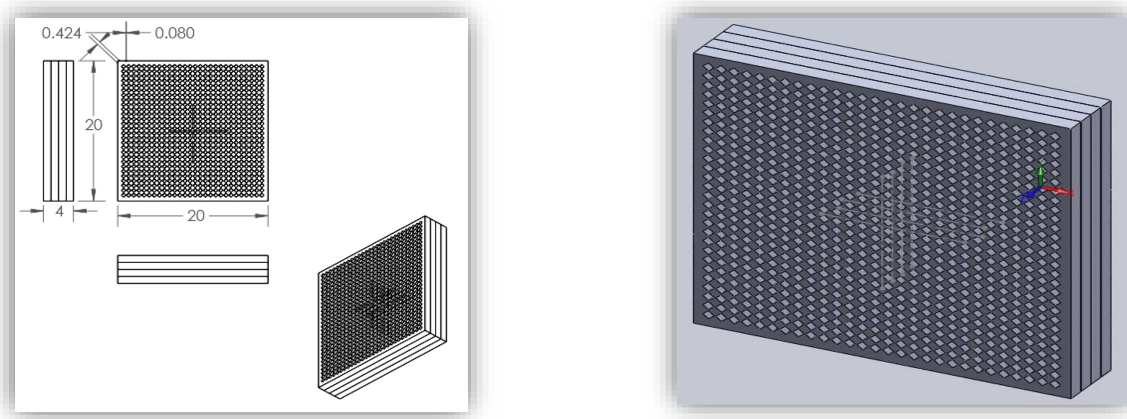

Fig.3: CAD model of Rhombus pore scaffold

Fabrication of polycarbonate porous scaffold
Manufacture of the scaffold specimens involves optimization of process parameters. Fabrication of porous scaffold procedure must produce a porous structure with a reproducible design, which can work as intended for a particular timeframe in the load carrying in the injured portion. The selection of manufacturing method can impact distinctive qualities of the porous scaffold, including required design, strength, biocompatibility, and biological properties.

Polycarbonate porous scaffold fabrication using SLA: Stereo lithography ViperSi2 system was used to fabricate the polycarbonate porous scaffold as shown in Fig. 4.

Fig. 4: Stereo lithography Viper Si2 System

It employed a vat of liquid ultraviolet curable photopolymer resin and an ultraviolet laser to build layers of parts one at a time. The resin used was polycarbonate material. For each layer, the laser beam traced a cross-section of the part pattern on the surface of the liquid resin. Exposure to the ultraviolet laser light cured and solidified the pattern traced on the resin and joins it to the layer below and finally the required scaffolds are obtained. The support structures were also used in order to act as a mounting device holding the part in position as it is built. To support overhanging cross section and to support unattached islands, supporting material which is same as built material is used. The fabricated scaffolds are shown Fig. 5.

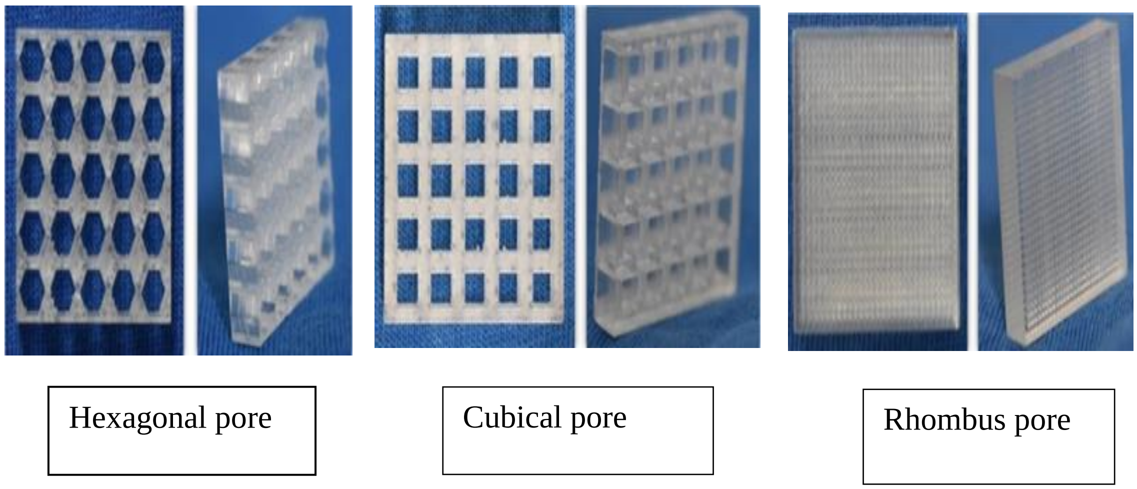

Fig. 5: Fabricated porous scaffold

The SLA method provides the best results and has good surface finish among the other rapid prototyping technology. The only drawback is that the strength of the fabricated component is less.

Testing of polycarbonate porous scaffold

The compression test was carried out on the scaffold in order to find the various properties of each scaffold, to compare with the properties of the human bone and to identify which model of the scaffold functions similar to the human bone. All scaffolds were mechanically tested in order to determine their mechanical properties. Axial compression tests with mechanical failure were carried out using a universal testing machine (Z50; Zwick Roell, Ulm, Germany) with a traverse velocity of 1.0 mm/min for all scaffolds. Values of applied load and displacement were continuously recorded during testing. The five samples of scaffolds fabricated were used to determine the mechanical property of the scaffolds using the compression test and the following values were obtained as shown in Table 2.

RESULTS

Table 2: Compressive stress of various scaffold designs

Specimen	Compressive stress (MPa)		
	Hexagonal pore model	Cubical pore model	Rhombus pore model
1	83.1	184.1	207.1
2	93.8	172.0	198.6
3	86.7	175.1	196.4
4	89.4	179.4	209.4
5	92.1	180.2	216.1

From the obtained values the three scaffold designs were compared. The graphical comparison of the compressive stress of the scaffolds along the percentage of deformation is shown Fig. 6.

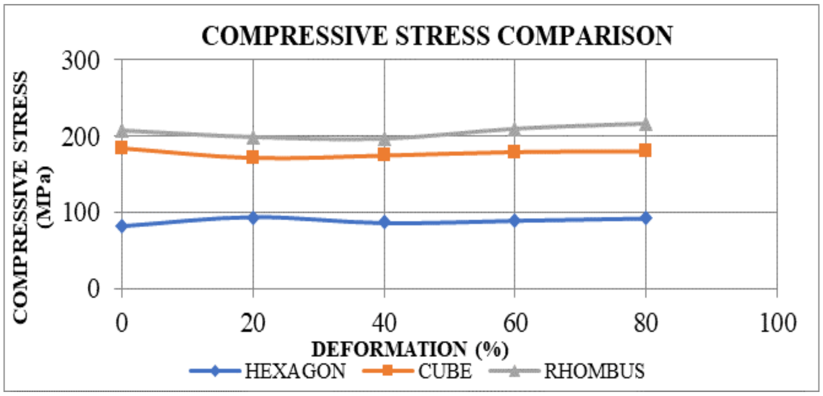

Fig. 6: Compressive stress comparison of the three scaffolds

The above graph indicates that the rhombus pore model exhibits the stress values around 200MPa¸which is closest to the compressive strength of human bone. Hence the rhombus pore model provides excellent mechanical load bearing strength when implanted for tissue regeneration in bones. Thus, the rhombus pore model is more efficient when compared among the three models of the scaffolds fabricated and so it is chosen for bone regeneration.

DISCUSSION

Rapid prototyping helps to facilitate bone formation in an injured human body portion in a lot quicker rate than any time in recent memory. The requirement for Rapid Prototyping Techniques (RPT) has begun to assume crucial job in fast item improvement cycle for complex shaped porous scaffold models. In this research work three types' unique models of porous scaffolds were designed, manufactured utilizing stereo lithography and tested. The research also proves that the SLA method provide the feasibility of fabricating porous structured components with complex architectures with good quality. Bisphenol-A Polycarbonate material provide better surface finish, 100% pore interconnectivity and new tissue formation of the fabricated scaffold. The SLA method offers the greater load bearing strength and good accuracy of porous scaffold. The investigation on porous structured scaffold manufacturing would be very much helpful in orthopedic applications.

CONCLUSION

In this research work polycarbonate was used as the resin to fabricate the scaffolds. Polycarbonate possessed clarity, high strength and impact resistance, good heat resistance, low water absorption, and biocompatibility. In future while fabrication of the scaffolds, Hydroxyl apatite (HA) has been planned to be mixed with the polycarbonate resin. Hydroxyl apatite can be found in teeth and bones within the human body. In this way, it is commonly utilized as a filler to replace the damaged bones.

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