PAPER 172 – SELECTION AND PORE DISTRIBUTION ANALYSIS OF BIOCOMPOSITE IMPLANTS FOR LOAD-BEARING BONE REPLACEMENT

H. K. Ibrahim [1,3*], M. S. Abolarin[1], A. S. Abdulrahman[2], O. Adedipe[1], U. G. Okoro[1]

[1]Department of Mechanical Engineering, School of Process, Infrastructure and Technology, Federal University of Technology Minna, Nigeria.
[2] Department of Material and Metallurgical Engineering, School of Process, Infrastructure and Technology, Federal University of Technology Minna, Nigeria.
[3] Department of Mechanical Engineering, Faculty of Engineering and Technology, University of Ilorin, Nigeria.
*Email: Ibrahim.kh@unilorin.edu.ng

ABSTRACT

Fabrication of biocomposites to promote bone growth through pore distribution and gradient formation for load-bearing bone replacement have gained attention due to their excellent mechanical properties and biocompatibility. This research study aims to investigate the selection and pore distribution analysis of homogenous, porous, and gradient biocomposite implants for load-bearing bone replacement. The study utilises powder metallurgy, scanning electron microscopy (SEM) and Image J software to produce and characterise the pore size distribution of the biocomposites, respectively. The software can segment the image to isolate the pores from the rest of the implant, measure the size of individual pores, and generate pore size distribution plots. The radar chart was adopted to compare and evaluate the mechanical strength of various biocomposite implants to identify the most suitable implant for load-bearing bone replacement. The findings of this study revealed the gradient and porous biocomposites exhibited desired mechanical properties with porosity of 20.67 and 27.72 % pore size up to 134 and 256 **μ**m, compressive strength of 162 and 95 MPa and compressive modulus of 30.42 and 28.3 GPa respectively**.** The SEM analysis, coupled with pore size distribution and porosity percentage measurements, offers valuable information for optimising the design and fabrication of biomaterials with enhanced properties. Radar chart analysis further contributes to a comprehensive evaluation of the implants' mechanical and physical characteristics.

KEYWORDS: Biocomposite, Pore, Mechanical, Properties, Selection and Image J

1. INTRODUCTION

Bone atrophy, also known as bone loss or osteoporosis, is a common condition characterised by decreased bone mass and deterioration of bone tissue. This condition often leads to weakened bones, increased fracture risk, and reduced quality of life for affected individuals (Poliakov *et al.,* 2019). In severe cases, load-bearing bones may become significantly compromised, necessitating implants for bone replacement (Bahraminasab and Farahmand, 2017). Traditional implants for load-bearing bone replacement are typically made from metallic materials such as titanium, cobalt chromium alloy or stainless steel. While these implants provide structural support, they often lack the necessary biological properties to promote bone growth and integration with the surrounding tissue (Cabezas-Villa *et al.,* 2018). Consequently, researchers and medical professionals have focused on developing biocomposite implants as an alternative solution to tailor the structural material for required mechanical and physical properties (Krishna and Suresh, 2022).

Biocomposite implants are engineered materials composed of organic and inorganic components. These materials possess a unique mechanical strength, biocompatibility, and bioactivity, making them ideal for load-bearing bone replacement and repair (Oshkour *et al.,* 2015). Biocomposite implants can provide both mechanical support and a favourable environment for new bone formation by mimicking the natural structure of bone. The selection of appropriate mechanical, physical properties and pore distribution is crucial for optimising the performance and functionality of these implants. A radar chart, a spider chart, is a graphical method utilised to select materials and process parameters in machining and manufacturing industries (Holota *et al.,* 2015; Wan *et al.,* 2013; Porter and Niksiar, 2018). This chart displays multivariate data as a two-dimensional chart of three or more quantitative variables represented on axes starting from the same point (Wan *et al.,* 2013). The relative position and angle of the axes in the radar chart provide the deviation degree of the actual value and the reference value of each index as required for the selection implant in the load-bearing application.

In selecting a load-bearing implant, biomechanical properties play a vital role in determining the implant's ability to withstand the mechanical stresses encountered during normal physiological activities. The implant's mechanical strength, stiffness, and fracture toughness must be carefully considered to ensure long-term stability and durability

(Mantripragada *et al.,* 2012; Moghadasi *et al.,* 2022). Additionally, the implant should have a similar or close modulus to the natural bone to minimise stress-shielding effects and promote proper load transfer to the surrounding tissue (Bahraminasab and Farahmand, 2017). The physical properties of biocomposite implants, including density, porosity, and surface characteristics, have been reported to be essential for bone integration (Jawad *et al.,* 2015). The implant should possess an appropriate density to match that of the host bone, which allows for efficient load transfer and prevents stress concentration at the implant-bone interface. The porosity in the implant facilitates nutrient diffusion, vascularisation, and cell infiltration, promoting bone ingrowth and enhancing the implant's long-term stability (Wo *et al.,* 2020).

Choy *et al.* (2015) revealed Ti/CaP biocomposites with a 1.67 atomic ratio have a porosity of 26%, pore size up to 152 um, compressive strength of 212 MPa and compressive modulus of 12 GPa. Wo *et al.* (2020) reported the micro-pore structure of porous Ti-6Al-4V scaffolds (pTi) produced 3D printing. The average pore size and porosity of pTi were obtained in the range of 300 ± 9 μm **-** 804 ± 10 μm and 42.7 ± 1.1 **-** 58.9 ± 1.3%, respectively. The pTi facilitated the adhesion and differentiation of osteoblast when pore size decreased, or porosity increased. Taniguchi *et al.* (2016) reported that the porous Ti-6Al-4V (pTi) implants fabricated from additive manufacturing with a porosity of 65% and pore size of 600 μm had better fixation ability and more significant bone ingrowth than those with pore sizes of 300 and 900 μm. Cetinel *et al.* (2019) fabricated Ti foams using the space holder method for bone substitute materials. The result shows that the foam samples with ~60% porosity had compressive strength comparable to that of cortical bone, and the samples with ~80% porosity displayed compressive strength similar to that of cancellous bone.

However, the pore size and distribution complexity affected the strength, especially the implants applied for load-bearing bone replacement. The Pore distribution analysis is a critical aspect of designing biocomposite implants. It is considered a key measure in many engineering calculations to quantify the complex geometry of the pore space (Oliveira *et al.,* 2020**;** Safari *et al.,* 2021). An optimal pore distribution allows for uniform bone ingrowth and vascularisation, enhancing the implant's integration with the host bone. Many researchers focused mainly on manufacturing implants with porosity percentages that revealed similar stiffness and bone ingrowth properties without considering another design pattern to correct the strength and stability of the implants. Therefore, this study aims to conduct a selection and pore distribution analysis of biocomposite implants for load-bearing bone replacement.

2. MATERIALS AND METHOD

2.1 Fabrication of Biocomposite Implants

The biocomposite specimens were produced in different design patterns, including dense, porous and gradient biocomposites using the powder metallurgy technique. The biocomposite samples were fabricated based on formulation compositions of pure titanium (P-Ti), cow bone-based hydroxyapatite (Ha), $CaCO_3$ (61.23Ti-18.41Ha-15.2$CaCO_3$) and constant volume fraction of Polyvinyl Alcohol (PVA) as binder and stabiliser. The biomaterial powders were mixed and blended using a Jar mixer for 20 min. Subsequently, the powder blends were poured into the fabricated cylindrical die with dimensions of 30mm height, 20mm internal diameter and 30mm outer diameter. The mixtures were uni-axially compacted using WEIBER P100HE electrically operated hydraulic press under a pressure of 400 MPa for 30 min. The compacted sample was ejected to obtain green biocomposite and preheated at a temperature of 200 °C to remove binder PVA), and lubricant as reported by Mara (2015). The wall of the circular die mould and top punch of the hydraulic press was adequately lubricated to avoid agglomeration of the specimen during ejection. The ejected samples were sequentially cleaned in deionised water containing several drops of acetone to eliminate contaminants. The preheated green biocomposite samples were further sintered under sintering temperatures of 800 °C for two hours in Murfle Furnance, and the heating rate was 10 °C/min. Similar procedures were adopted for the fabrication of porous biocomposite specimens. However, the space holder (SH) method was utilised to fabricate porous biocomposite samples with reported ranges of space holders in the literature for optimal porosity (Cetinel et al. 2018). The fabrication involves mixing of biomaterial compositions of 59.31Ti-16.19 (Ha+$CaCO_3$)-9.4 % of Ammonium Bicarbonate with 100 um particle size as space holder (SH) material and decomposed at 110 °C. Followed by the addition of binder, stabiliser and lubricant and poured in cylindrical die mould. The green porous samples were compacted and sintered. The gradient biocomposite (GB) sample was produced from the different compositions (100Ti, 61.23Ti-18.41Ha-15.2$CaCO_3$ and 59.31Ti-16.19 (Ha+$CaCO_3$)-9.4SH) biomaterial powders and separately poured in the die mould of 20mm internal diameter and 30mm height dimensions after blending processes using SNE FOURE 28A2092 Jar Mixer, for 20 minutes. Three separate layers formed were stacked and compacted uni-axially using WEIBER P100HE electrically operated hydraulic press with 400 MPa to obtain green-gradient composite biomaterial samples. The wall of the circular die mould and the top punch of the hydraulic press was lubricated correctly to avoid