Multi-scale Modelling and Mechanical Characterization of Porous Hierarchical Hydroxyapatite
Rationale

Bone grafting is traditionally the procedure used to replace missing bone or repair bone defects (Czitrom & Gross, 1992; Meeder & Eggers, 1994). Moreover, grafts are used to reinforce the repaired area by encouraging new bone growth into the defect site. Ideally the newly formed bone would, with time, penetrate and replace much of the graft through a process known as remodelling (Sikavitsas et al., 2001), a phenomenon in which old bone is sequentially removed by phagocytic cells.

Bone surgeons have, thus far, implemented three techniques for bone repair: autografting (healthy bone tissue taken from the patient’s own body), allografting (healthy bone tissue taken from a donor) and synthetic bone graft substitutes (artificial biomaterial similar to bone). Autografting is considered the ‘gold’ standard, however the volume of bone that can be safely harvested is limited, and the additional surgical procedure may be complicated by donor site pain and morbidity. Modern allografting using materials stored at regulated bone banks overcome these difficulties, however, healing can be unpredictable and there are concerns regarding disease transfer (Le Guéhennec et al., 2004; Hing et al., 2007; Togawa et al., 2004). In view of the limitations of biologically-derived grafts, synthetic bone substitutes have been developed and clinically used (Le Guéhennec et al., 2004). The aim of such substitutes is to interact in an appropriate manner with their bio-surroundings and mimic the properties of bone (Guéhennec et al., 2004).

The interest in the use of synthetic biomaterials as scaffolds for bone implants has been ever so growing (Carlisle, 1970; Hing, 2005). More significantly, hydroxyapatite (HA) has been widely reported due to its chemistry, molecular structure, and mineral content being similar to that of mineral bone phase (Hing, 1996; Hing et al., 1999); as well as having optimal biocompatibility, bioactivity, osteoconductivity and partial osteoinductivity (Cordell et al., 2009). Hydroxyapatite comprises approx 70 wt% (40 vol%) of bone and is responsible for its rigidity and compressive strength (Hench, 1993; Wilson, 1993). There are two main types of HA; dense and porous. Whilst dense HA is required for cell vitality and mechanical strength, it has been shown that porous material, contributing to cell and ion transport, is vital for tissue ingrowth and consequently a key factor in successful bone graft substitutes (Hornez et al., 2007; Woodward, 2007).

A novel approach of substituting silicon into porous HA has also been shown to have “significant influence on the rate and pattern of bone formation in vivo” (Carlisle, 1970; Shors & Holmes, 1993; Gibson et al., 2002; Hing et al., 2004, 2005; Patel et al., 2002; Manzano et al., 2009). Researchers reported silicon-substituted HA provided optimal, interconnected porous graft to accelerate bone formation. Hornez et al., (2007) investigated porosity levels of HA and concluded that among micro-, meso-, and macro- porosities, microporosity showed the highest amount of cell proliferation. Hing et al., (1999) and Peng et al., (2010) reported that by allowing cellular infiltration of micropores, there is an improvement to the mechanism by which cells attach to the surface of porous HA. This, in turn, increases biological fixation; so improved mechanical interlock between cells and material.

Nonetheless, it is yet not well understood how the macrostructure and microstructure of HA interact with each other to promote osteointegration and how the mechanical properties of trabecular bone can be affected by a change in the type and extent of HA porosity. Moreover the lack of standardisation in characterizing substituted material and insufficiency regarding experimental methods employed makes comparison difficult.

In retrospect, creating a numerical experimental model will provide a technique for the variation and assessment of microstructure; thus enabling an accurate and reliable prediction of mechanical characterization with changes in porosity.
Aims & Objectives

Aim
To predict the porosity-dependent mechanical performance of porous Si-HA by creating and validating computational models at macro- and micro- scales.

Objectives
In the present study, manufacturing of porous microstructural Si-HA specimens of various geometries (i.e. discs, pellets, cylinders) and porosity levels, will be performed for characterisation purposes. Porous macrostructural Si-HA specimens will be acquired by courtesy of Dr Hing.

Structural characterisation by means of Scanning Electron Microscopy (SEM), Archimedes’ Principle Density and X-ray Microcomputed Tomography (Micro-CT) will be conducted to determine pore characteristics, pore connectivity and porosity.

Further, material characterisation by means of Compression and Brazilian testing will be conducted to determine the mechanical properties as well as the local and gross strains of the microstructural Si-HA specimens.

A unique specimen identifier system will be formed for the correlation of structural and material testing in part-fulfilment of the stated aim.

The structural data will be used to produce idealised computational models of porous Si-HA at micro and macro scales that will effectively predict the mechanical behaviour of HA.
Key Findings

Structural Characterisation

From structural characterisation of the hydroxyapatite samples, it has been noted that the manufacturing technique does not produce homogeneous structures. Density, porosity and pore geometry is highly variable throughout batches of the same milling time as well as between batches of different milling times. This can be seen in Fig. 1, where the pore geometry, particle size and pore distribution is shown to be highly variable. Micro-CT is a vital tool when characterising macroporous structures as it allows for in-depth analysis of porosity of both open and closed pores, something which is not readily available via other characterisation methods. Fig. 2 shows one of the obtained macroporous HA images. Densities of specimens were calculated using the Archimedes’ Principle. The results showed that as the total porosity decreases apparent density increases. The total porosities of the disc specimens were 32.72±1.6%, 28.72±0.93%, 22.86±2.9 % and the apparent densities were 2.12±0.053, 2.24±0.029, 2.43±0.094 g/cm$^3$ for 10, 20, and 40 minutes milling time respectively.

Mechanical Characterisation

It has been observed and concluded from the results obtained that a general trend of increasing diametral tensile strength occurs with a decreased value of percentage porosity (Fig. 3) within the tested specimens. It was evident that a large scatter of values existed for diametral tensile strength across different treatment groups. This is an inherent characteristic of ceramics; if a larger testing number had been studied a more distinct trend could have been observed. It was noted form that the range of scatter occurred across the six treatment groups. This showed that the mechanical behaviour of the specimen varied significantly on each manufacturing day. This is supported by the structural characterisation, which found that the pore morphology changed within each specimen on each consecutive day. This was a major limitation to which meant that a proper correlation between the data values could not have a distinct trend as noted by other researchers (Fang et al., 1992, and Evis and Ozturk, 2008). As noticed in studies done by many other previous authors, the ultimate compressive strength (UCS) was inversely related to the porosity. Even then, due to the variation that can be seen on Figs 3 & 4, more trials with improved specimens need to be done in order to come to a conclusion.

Computational Modelling

The obtained effective elastic modulus for the Macroporous simulation (Figs. 7 & 8 left) was 7.25 MPa. At a similar macroporosity (55%), Lacroix et al., (2006) obtained an effective compression modulus estimated at 7.14 MPa for their macroporous CaP model. Therefore, contrary to authors such as Hu et al., (2009), the apparent mechanical properties of irregular structures can be effectively modelled by finite element idealisation.

The analyses on the microstructure models (Fig. 5 & 6) showed that the overall mechanical properties were influenced by the stress distribution, porosity (volume fraction) and material distribution. The model exhibited localisation along the plane parallel to the y-axis (axis of load displacement) and also at the sites of pore accumulation. This coincided with the distribution of stresses $\sigma_y$ with the distribution of elastic strain.

Evaluation of the microporous material properties into the macroporous model showed that mechanical failure was delayed and inelastic deformation was prolonged. Equally as key, it was found that when the highest microporosity (37.2%) material properties were used the stress concentration factor and principal stresses were reduced (Fig. 8, right). This suggested that a small difference between the macroporosity and microporosity of a structure enhances HA mechanical resistance to compressive loads.

Finally the computational results showed that the mechanical integrity of the macroporous model is much inferior to the comparable microporous model as shown by the calculated elastic moduli: 7.25 MPa and 42-78 MPa for the macroporous and microporous models respectively.
Results

Structural Characterisation

Figure 1. Comparisons of microstructure between mill times. 1) 10 minute 2) 20 minute 3) 40 minute. The gray bar represents 50 µm in length.

Macroporous Structure

Figure 2. Representative Micro CT slice of one macroporous sample at 7.2 µm resolution
Mechanical Characterisation

**Diametral Testing**

![Graph illustrating Variation in the Diametral Tensile Strength (MPa) over the 6 Treatment Groups in relation to % Porosity](image)

**Figure 3.** Graph illustrating Diametral Tensile Strength (MPa) against % Porosity for six Treatment Groups

**Compression Testing**

![Graph showing Relationship between Ulimate Compressive Strength (UCS) and Porosity](image)

**Figure 4.** Relationship between the ultimate compressive strength and the porosity of the small SiHA samples regardless of the milling times.
Computational Modelling

Microporous modelling:

Figure 5. Model 1: A) Selected region (red box) on SEM micrograph. B) Idealised model of selected region.

Figure 6. Max principal strain distribution in Model 1 at porosity of 28.72% (left); effect of porosity of the idealised hydroxyapatite scaffold material on the strain-strain curves. Higher porosities lowered the mechanical properties of the modelled structure (right).
Macroporous modelling:

Figure 7. Arbitrarily selected area of porous HA macrostructure showing congruence of the idealised FEM model (right) and the Micro-CT image (left). A total of 14 mean pore diameters were applied to the FEM model using the multiple-average pore diameter data.

Figure 8. $\sigma_1$ contours of the MaP model under applied compressive 0.005% strain. Highest $\sigma_1 = 2.109 \times 10^{-1}$ MPa (left); results of stress intensity factors for the 4 material simulations (right). Note that MaP refers to the simulation of the macroporous model using macroporous material data, whereas MiP refers to the simulation of the macroporous model using microporous material properties.
References


