



4th International Conference on Tissue Engineering, ICTE2015

Tensile and Shear Stress Evaluation of Schwartz Surfaces for Scaffold Design

Henrique A. Almeida^{a*}, Paulo J. Bártolo^b

^a School of Technology and Management, Polytechnic Institute of Leiria, Portugal

^b School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK

Abstract

Tissue engineering represents a new, emerging interdisciplinary field involving combined efforts of several scientific domains towards the development of biological substitutes to restore, maintain, or improve tissue functions. Scaffolds provide a temporary mechanical and vascular support for tissue regeneration while shaping the in-growth tissues. These scaffolds must be biocompatible, biodegradable, with appropriate porosity, pore structure and pore distribution and optimal structural and vascular performance, having both surface and structural compatibility. Surface compatibility means a chemical, biological and physical suitability to the host tissue. Structural compatibility corresponds to an optimal adaptation to the mechanical behaviour of the host tissue. The design of optimised scaffolds based on the fundamental knowledge of its macro microstructure is a relevant topic of research.

This research proposes the use of geometric structures based on Triple Periodic Minimal Surfaces, namely, Schwartz geometries for tensile and shear stress applications. Geometries based on these surfaces enables the design of vary high surface-to-volume ratio structures with high porosity and mechanical/vascular properties. Numerical simulations on the Schwartz surfaces were performed considering two geometric variations: surface thickness and surface radius construction. The results demonstrate how the mechanical (Elastic and Shear) cell stimuli vary with the geometric variations of the Schwartz surfaces.

© 2015 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of IDMEC-IST

Keywords: Tissue Engineering; Scaffolds; Schwartz Surfaces; Numerical Simulation; Structural Analysis.

* Corresponding author. Tel.: +351 244 820 300; fax: +351 244 820 310.

E-mail address: henrique.almeida@ipleiria.pt

1. Introduction

The loss or failure of an organ or tissue is a frequent, devastating, and costly problem in health care. The need for substitutes to replace or repair tissues or organs due to disease, trauma, or congenital problems is overwhelming. Organ or tissue loss is currently treated by transplanting organs from one individual to another or performing surgical reconstructions by transferring tissue from one location in the human body into the diseased site.

Tissue engineering represents a new, emerging interdisciplinary field involving combined efforts of biologists, engineers, material scientists and mathematicians towards the development of biological substitutes to restore, maintain, or improve tissue functions (Bártolo et al, 2011; Bártolo et al, 2009; Gibson, 2005).

Most strategies in tissue engineering have focussed on using biomaterials as scaffolds to direct specific cell types to organise into three-dimensional structures and perform differentiated functions. The three most common strategies which have been adopted for the creation of new tissues are (Bártolo et al, 2009):

- *Cell self-assembly*, which corresponds to the direct *in vivo* implantation of isolated cells or cell substitutes and it is based on cells synthesizing their own matrix. This approach avoids the complications of surgery and allows replacement of only those cells that supply the needed function. The main limitations include immunological rejection and failure of the seeded cells.
- *Acellular scaffold*, which is based on the ingrowth of tissue cells into a porous material, loaded with growth factors or any other therapeutic agent.
- *Cell-seeded temporary scaffolds*, which is based on the use of a temporary scaffold that provides a substrate for the implanted cells and a physical support to organize the formation of the new tissue. In this approach, transplanted cells adhere to the scaffold, proliferate, secrete their own extracellular matrices and stimulate new tissue formation.

These scaffolds are often critical, both *ex vivo* as well as *in vivo*, as they serve some of the following purposes (Bártolo et al, 2009; Leong *et al*, 2008; Leong *et al*, 2003): allowing cell attachment, proliferation and differentiation, delivering and retaining cells and growth factor; enabling diffusion of cell nutrients and oxygen, as well as an appropriate mechanical and biological environment for tissue regeneration in an organised way.

To achieve these goals, an ideal scaffold must satisfy some biological and mechanical requirements (Bártolo *et al*, 2007). The biological requirements are: biocompatibility (the scaffold material must be non-toxic and allow cell attachment, proliferation and differentiation), biodegradability (the scaffold material must degrade into non-toxic products), controlled degradation rate (the degradation rate of the scaffold must be adjustable in order to match the rate of tissue regeneration) and appropriate macro and microstructure of pores and pores shape to allow tissue ingrowth and vascularisation.

The mechanical and physical requirements are: sufficient strength and stiffness to withstand stresses in the host tissue environment, adequate surface finish to guarantee that a good biomechanical coupling is achieved between the scaffold and the tissue and easily sterilised either by exposure to high temperatures or by immersing in a sterilisation agent, remaining unaffected by either of these processes (Almeida and Bártolo, 2010).

The design of optimised scaffolds for tissue engineering is a relevant topic of research. Previous work, (Almeida and Bártolo, 2008a; Almeida and Bártolo, 2008b; Almeida *et al*, 2007a; Almeida *et al*, 2007b), developed a strategy to optimize both mechanical and vascular behaviour of both polymeric and ceramic scaffolds. The evaluation of scaffold's porosity and mechanical properties was performed for a range of regular geometries. In this paper, triple periodic minimal surfaces are explored to design more biomimetic scaffolds.

2. Triply Periodic Minimal Surfaces

2.1. Definition

Hyperbolic surfaces have attracted the attention of physicists, chemists and biologists as they commonly exist in natural structures. Amongst various hyperbolic surfaces, minimal surfaces (those with mean curvature of zero) are the most studied. If a minimal surface has space group symmetry, it is periodic in three independent directions. These surfaces are known as Triply Periodic Minimal Surfaces (TPMS). In nature, TPMS are found in lyotropic

liquid crystals, zeolite sodalite crystal structures, diblock polymers, soluble proteins in lipid-protein water phases and certain cell membranes (Larsson *et al*, 2003; Andersson, 1983; Scriven, 1976). TPMS allow very high surface-to-volume ratios and provide good analytic description of highly porous structures.

2.2. Schwartz TPMS Primitives

An important sub-class of triply periodic minimal surfaces are those that partition space into two disjoint but intertwining regions that are bi-continuous. An example of such surfaces includes the so-called Schwartz primitives (figure 2) for which, each disjoint region has a volume fraction equal to $\frac{1}{2}$.

The periodic Schwartz primitive surface is given by (Wang, 2007):

$$\phi(\mathbf{r}) = A_P \left[\cos(2\pi x/\lambda_x) + \cos(2\pi y/\lambda_y) + \cos(2\pi z/\lambda_z) \right] = 0 \quad (1)$$

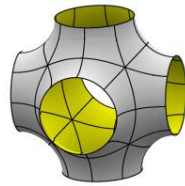


Fig. 1. Schwartz TPMS primitive.

Two important parameters can be used as modelling control constraints: thickness and radius. Figures 2 and 3 illustrate the effect of these parameters on the Schwartz primitives (*P*-minimal surfaces) obtained structures.

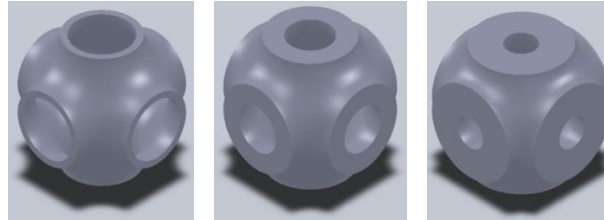


Fig. 2. P-minimal surfaces obtained through thickness variation with constant surface radius.

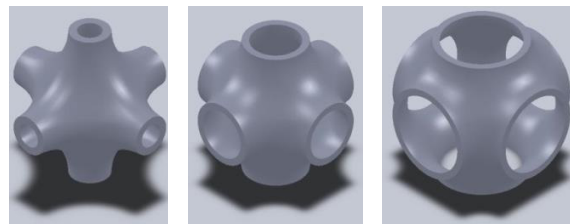


Fig. 3. P-minimal surfaces obtained through radius variation with constant surface thickness.

3. Mechanical Simulation

The main goal for simulating the scaffold mechanical behaviour is to evaluate the porosity dependence on the elastic modulus. For a given unit block with a specific open pore architecture, boundary and loading conditions considered for evaluating mechanical properties, are shown in figure 4:

- For the numerical computation of the elastic modulus (figure 4.a)), a uniform displacement in a single direction is considered (the X direction), which is equivalent to the strain on the same direction (ϵ_x), imposed to a face of the block (Face A). The opposite face (Face B) of the scaffold unit is constrained and unable to have any displacement. The average reaction force produced on Face B is used to determine the elastic modulus, due to the imposed displacement.
- For the numerical computation of the shear modulus (figure 4.b)), a uniform displacement in a single direction is considered (the Y direction), which is equivalent to the strain on the same direction (γ_{xy}), imposed to a face of the block (Face B). The opposite face (Face A) of the scaffold unit is constrained and unable to have any displacement. The two lateral faces (Faces C) are also constrained and unable to have any displacement in the X direction. The average reaction force produced on Face A is used to determine the shear modulus, due to the imposed displacement.

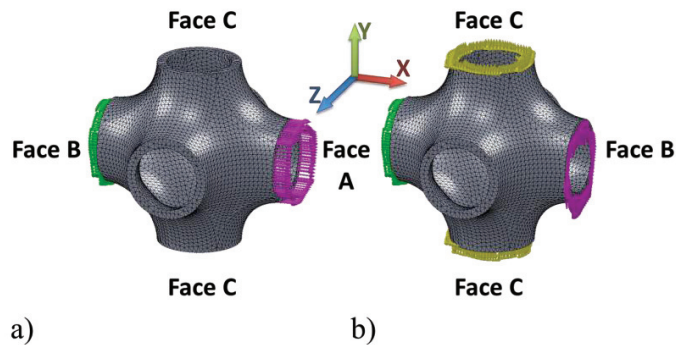


Fig. 4 Loads and constraints for the numerical analysis of scaffolds under a a) tensile solicitation and b) shear solicitation.

3.1. Results

Mechanical computer simulations were carried out to evaluate the effect of both the *P*-minimal surface thickness and radius variation. The material considered for simulation purposes is PCL, that is a semicrystalline biodegradable polymer having a melting point of ~ 60 °C and a glass transition temperature ~ -60 °C. The elastic modulus of PCL was considered to be 400 MPa.

Figure 5 illustrates how porosity decreases with the *P*-minimal surface thickness. Regarding the effect of the *P*-minimal surface radius variations, figure 6 shows that porosity decreases till a threshold value for the surface radius from which starts to increase.

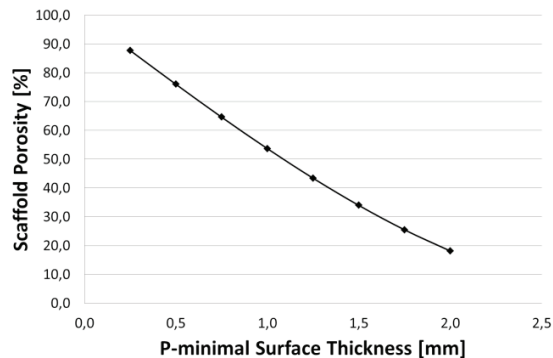


Fig. 5. Variation of the scaffold porosity with the *P*-minimal surface thickness.

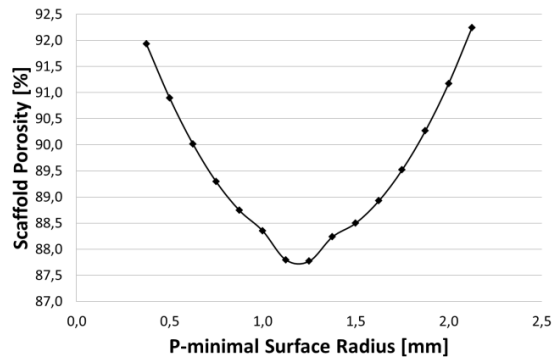


Fig. 6. Variation of the scaffold porosity with the P-minimal surface radius.

Results for the tensile solicitations, considering both the thickness and radius variations, are shown in Figures 7 to 10. Figure 7 shows that the elastic modulus increases with thickness. A linear dependence between the scaffold porosity and the elastic modulus was obtained as observed in Figure 8.

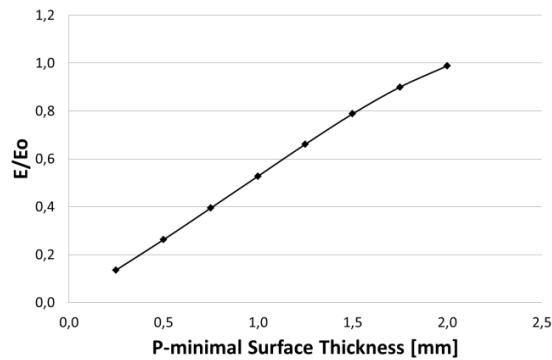


Fig. 7. Variation of the elastic modulus with the P-minimal surface thickness.

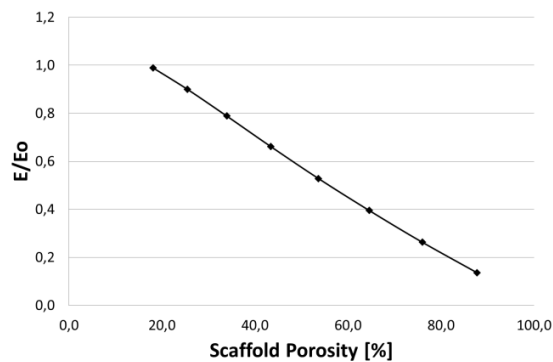


Fig. 8. Variation of the elastic modulus with porosity.

Regarding the effect of the *P*-minimal surface radius variations, the elastic modulus decreases by increasing the *P*-minimal surface radius as shown by figure 9. As the porosity and the radius have a hyperbolic behaviour, the same was observed for the elastic modulus (figure 10). Therefore we may decrease or increase the elastic modulus of the scaffold while maintaining high porosity values.

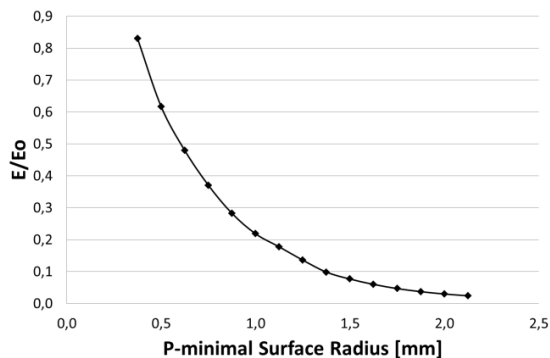


Fig. 9. Variation of the elastic modulus with the P-minimal surface radius.

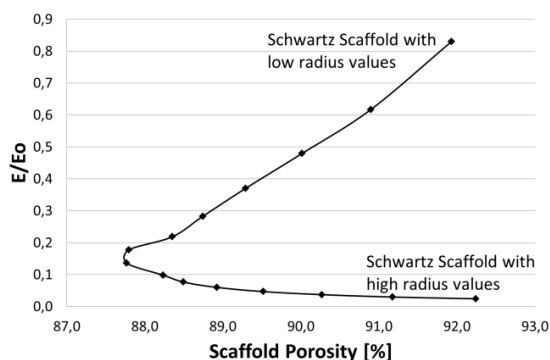


Fig. 10. Variation of the elastic modulus with the porosity.

Results for the shear solicitations, considering both the thickness and radius variations, are shown in Figures 11 to 14. Figure 11 shows that the shear modulus ratio increases with thickness. This figure also demonstrates that the P-minimal surface presents a higher shear modulus behaviour compared to the material’s reference shear modulus. In other words, the P-minimal surface increases the shear performance above reference for high thickness values. A linear dependence between the scaffold porosity and the shear modulus ratio was obtained as observed in Figure 12.

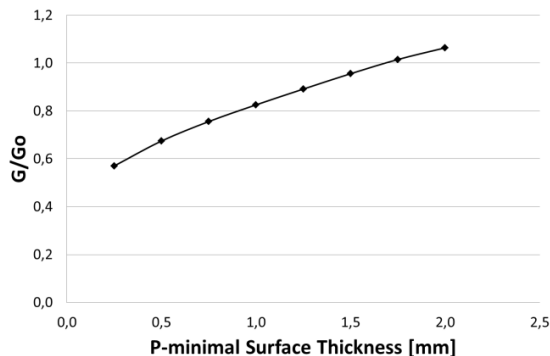


Fig. 11. Variation of the shear modulus ratio with the P-minimal surface thickness.

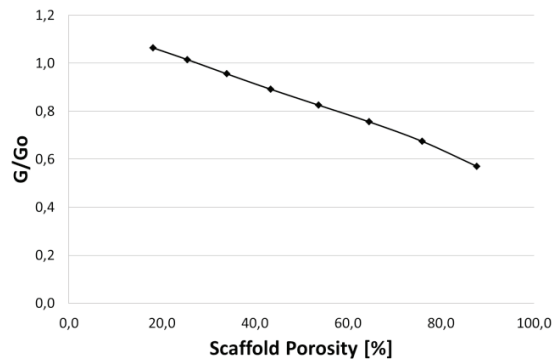


Fig. 12. Variation of the shear modulus ratio with porosity.

The shear modulus ratio increases then begins to decrease as the P-minimal surface radius increases, as shown by Figure 13. In spite of the porosity and the radius having a hyperbolic behaviour, the shear modulus ratio with the P-minimal surface radius has a sinusoidal behaviour, while the shear modulus ratio with the porosity has an approximated hyperbolic behaviour (Figure 14). In this case, we may decrease or increase the shear modulus of the scaffold while maintaining high porosity values.

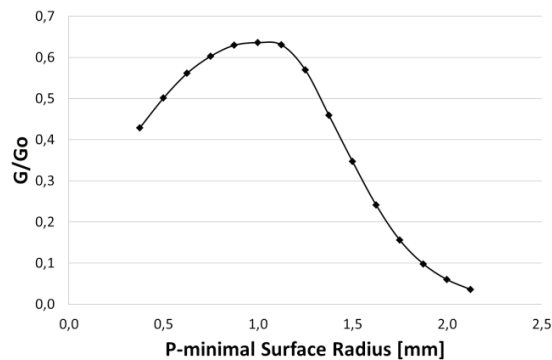


Fig. 13. Variation of the shear modulus ratio with the P-minimal surface radius.

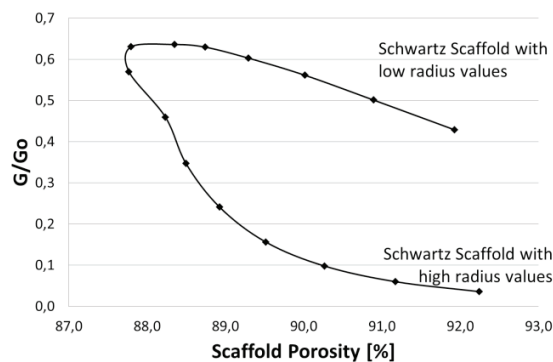


Fig. 14. Variation of the shear modulus ratio with the porosity.

4. Conclusions

Understanding the mechanical and transport properties of highly porous scaffolds from a knowledge of its microstructure is a problem of great interest in tissue engineering. In this paper, porous scaffolds are designed and its shear mechanical behaviour simulated using Triple P-minimal surfaces, namely Schwartz geometries.

For the tensile solicitations, the results show that porosity decreases with the P-minimal surface thickness, decreasing also till a threshold value for the P-minimal surface radius. From this threshold value, porosity starts to increase. The elastic modulus increases with the P-minimal surface thickness and decreases by increasing the P-minimal surface radius.

Regarding the shear solicitations, the results show that porosity decreases with the P-minimal surface thickness, decreasing also till a threshold value for the P-minimal surface radius. From this threshold value, the porosity then starts to increase. The shear modulus ratio increases with the P-minimal surface thickness and presents an approximated hyperbolic behaviour by increasing the P-minimal surface radius.

By using triple periodic surfaces in scaffold design for tissue engineering applications, it is possible to use highly porous structures with optimum mechanical properties.

References

- Almeida, H.A. and Bártolo, P.J., 2010 “Topological optimization of scaffolds for rapid prototyping”, *Medical Engineering & Physics*, 32:775-783
- Almeida, H.A. and Bártolo, P.J., 2008a “Computer Simulation and Optimisation of Tissue Engineering Scaffolds: Mechanical and Vascular Behaviour”, 9th Biennial ASME Conference on Engineering Systems Design and Analysis (ESDA2008), Technion University, Haifa, Israel.
- Almeida, H.A. and Bártolo, P.J., 2008b “Scaffolds Designed by Applying CAD/CAE Techniques”, *Polymers & Moulds Innovations (PMI2008)*, University College, Ghent, Belgium.
- Almeida, H.A., Bártolo, P.J. and Ferreira, J., 2007a “Design of Scaffolds Assisted by Computer”, *Modelling in Medicine and Biology VII*, edited by C.A. Brebbia, Wit Press, pg. 157-166.
- Almeida, H.A., Bártolo, P.J. and Ferreira, J., 2007b “Mechanical Behaviour and Vascularisation Analysis of Tissue Engineering Scaffolds”, *Virtual and Rapid Manufacturing*, edited by P.J. Bártolo et al, Taylor&Francis, pg. 73-80.
- Andersson S., 1983 “On the description of complex inorganic crystal structures”, *Angew Chem Int Edit*; 22(2):69-81.
- Bártolo, P.J., Domingos, M., Gloria, A., Ciurana, J., 2011, “BioCell Printing: Integrated automated assembly system for tissue engineering constructs”, *CIRP Annals Manufacturing Technology*, 60(1):271-274.
- Bártolo, P.J., Chua, C.K., Almeida, H.A., Chou, S.M., Lim, A.S.C., 2009, “Biomufacturing for tissue engineering: present and future trends”, *Virtual and Physical Prototyping*, 4:203-216.
- Bártolo, P.J., Almeida H. and Laoui, T., 2007, “Rapid prototyping & manufacturing for tissue engineering scaffolds”, *International Journal of Computer Applications in Technology*, 36(1):1-9.
- Gibson, L.J., 2005, “Biomechanics of cellular solids”, *Journal of Biomechanics*, 38(3):377-399.
- Larsson M, Terasaki O, Larsson K., 2003 “A solid state transition in the tetragonal lipid bilayer structure at the lung alveolar surface”, *Solid State Sci*, 5(1):109-14.
- Leong K.F., Cheah C.M. and Chua, C.K., 2003, “Solid freeform fabrication of three-dimensional scaffolds for engineering replacement tissues and organs”, *Biomaterials*, 24(13):2363-2378.
- Leong, K.F., Chua, C.K., Sudarmadja, N., Yeong, W.Y., 2008. “Engineering functionally graded tissue engineering scaffolds”, *Journal of Mechanical Behaviour of Biomedical Materials*, 1:140-152.
- Lord, E.A. and Mackay, A.L., 2003 “Periodic minimal surfaces of cubic symmetry”, *Current Science*, 85(3):346-362.
- Scriven L.E., 1976 “Equilibrium bicontinuous structure”, *Nature*, 263(5573):123-5.
- Wang, Y., 2007 “Periodic surface modeling for computer aided nano design”, *Computer-Aided Design*, 39:179-189.