FINITE ELEMENT MODEL OF POLYACRYLAMIDE HYDROGEL TO ASSESS OPTIMUM THICKNESS FOR COMPRESSION APPLICATIONS

RMRC Udayanandana[1*], KMTD Gunasekara[2], P Silva[3]

[1] Faculty of Engineering, General Sir John Kotelawala Defence University, Sri Lanka.

[2]Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

[3]InterSafe (Australia), The University of Queensland, Brisbane, Queensland, Australia.

[1]ruwanu@kdu.ac.lk, [2]thilinidg@sjp.ac.lk, [3]puji.silva@gmail.com

ABSTRACT

Hydrogels are emerging as a biomaterial in the field of tissue engineering. The low mechanical strength is one of the main challenges in load-bearing biomaterial applications such as knee cartilage and intervertebral disc replacement. In this research, the applicability of polyacrylamide hydrogel as an insole material for diabetic patients with foot-related issues was considered. Optimum thickness in these applications is a key factor in deciding the cushioning performance. The optimized thickness of polyacrylamide hydrogel was determined through uniaxial compression and finite element modelling and analysis methods. The hydrogel was modelled as hyper-viscoelastic material by using Abaqus finite element analysis software. The compression test data was used to develop the hyperelastic Ogden model and stress relaxation test data to develop the model's viscoelastic parameters. The developed finite element model was validated with pressure insole test data. The validated finite element model was used to investigate the pressure distribution properties and to optimize the thickness suitable for compression load-bearing insole applications. The results indicated that the thickness of 6 mm to 8 mm polyacrylamide hydrogel was capable of reducing peak pressure below the upper threshold value of 200 kPa.

KEYWORDS: *Hydrogels, Hyper-viscoelastic, Pressure insole, Finite element analysis*

1. INTRODUCTION

Hydrogels consist of a three-dimensional hydrophilic polymer network with the ability to contain a large amount of water. This specific structure of hydrogels has the potential for use as a synthetic biomaterial in tissue engineering and biomedical applications. The applications of hydrogels in the biomechanical field include replacement materials for body tissues, knee cartilage, and intervertebral discs (Silva et al., 2005; Ghorbanoghli and Narooei, 2019).

The peak pressure acting on the bare foot of a healthy person with neutral feet was 503.8±9.32 kPa (Fernández-Seguín et al., 2014) and this can go up to 738.6 ± 322.3 kPa in patients with a history of diabetic foot ulcer (Yavuz et al., 2016). A flat insole (50 Shore A EVA) is capable of reducing the peak pressure to a level of 240 kPa (Martinez-Santos et al., 2019). An upper limit of plantar pressure value of 200 kPa was established by IWGDF guidelines (2019) for the prevention of ulcer recurrence. The finite element analysis enables efficient parametric evaluations for different shapes and material modifications, without needing to fabricate and test the samples in a series of patient trials. Researchers (Lemmon et al., 1997; Chen et al., 2003; Cheung and Zhang, 2005) have used FEA to study what effects orthotic thickness and stiffness have on plantar soft tissue and plantar pressure distribution. Commercial Abaqus FEA software has been commonly used to model soft tissues and tissue-like behaviour (Castro et al., 2018) and has been successfully used for the analysis of foot-insole interaction (Cheung and Zhang, 2005; Goske et al., 2006). The development of the visco-hyperelastic numerical material model used experimental tests such as compression, creep, and stress relaxation (Briody et al., 2012) and to develop the initial hyperelastic material model such as the Ogden hyperfoam material model (Ogden 1972). The developed finite element model can be used for deciding the optimized parameters without conducting excessive experiments. The finite element model will vary based on the chemical composition and the test arrangement used.

**Corresponding Author: ruwanu@kdu.ac.lk (RMRC Udayanandana)*

The objectives of this research were to develop a finite element model of polyacrylamide (PAAm) hydrogel by using the compression and stress relaxation experimental data and to validate the finite element model by using pressure insole test data to find the optimum thickness for cushioning and load-bearing application under foot.

2. METHODOLOGY

The development of PAAm hydrogel was described by the authors (Udayanadana et al., 2019). The hydrogel sample with 60±0.5 mm diameter and 5 mm thickness was compressed between two plates as shown in Figure 1(a). The FEA model was created as unconfined compression and the element type was CAX4H (4-node bilinear axisymmetric quadrilateral, hybrid, constant pressure) (Abaqus, 2014) (Figure 1(b)). The Ogden and polynomial curves were compared with the experimental curve and the Ogden N=2 curve was selected by considering the stability (Figure 1(c)). The Ogden hyperelastic material model coefficients were calculated in Abaqus FEA software based on experimental test data. The viscoelastic material model curve fits with the stress relaxation curve indicating the viscoelastic behaviour of the sample (Figure 1(d)).

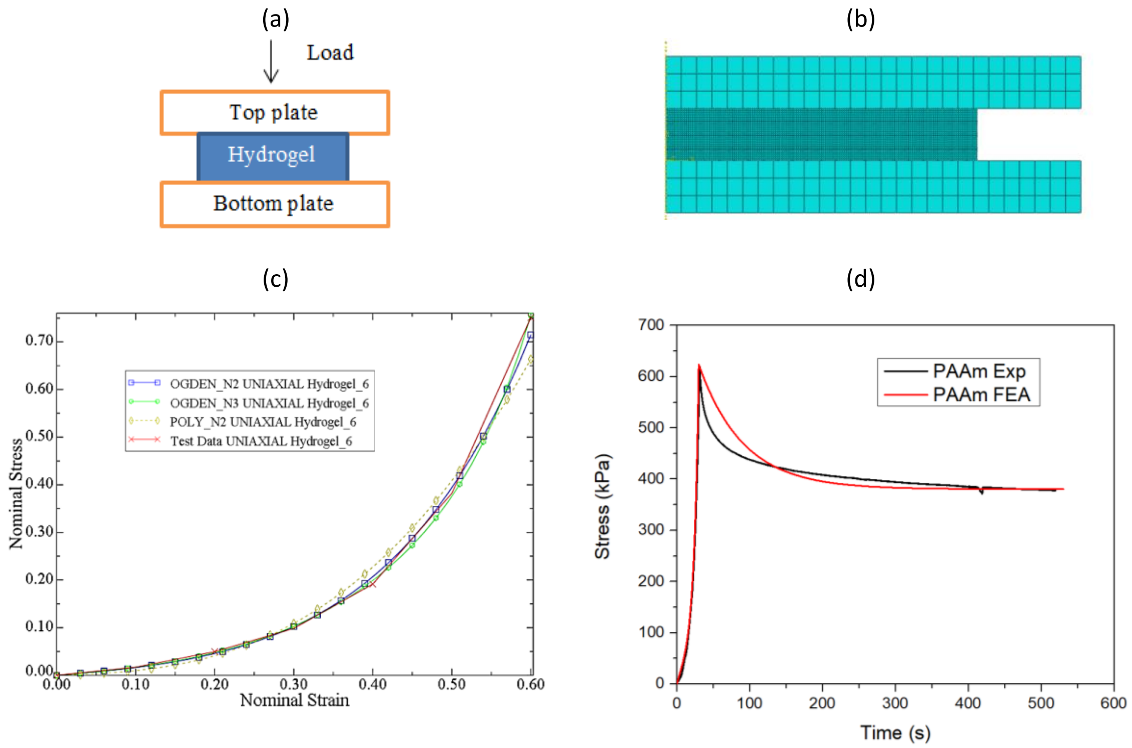

Figure 1: (a) The experimental setup (b) The 2D axisymmetric FEA model arrangement used in parameter identification (c) The Ogden, polynomial, and experimental curves. (d) Stress relaxation curves fitting to identify relaxation parameters

The test arrangement for indenter testing is shown in Figure 2. The pressure insole was kept between the indenter and hydrogel sample to measure the pressure distribution during compression. A 2D axisymmetric finite element model was developed to match experiment setup (Figure 3 (a)). The top surface of hydrogel and pressure insole contact was considered frictionless due to the smooth surface of stainless steel indenter contact with the hydrogel surface and the bottom surface was considered as rough due to rough surface of bottom plate contact with hydrogel bottom surface.

Figure 2: Test arrangement during testing with indenter and Tactilus pressure sensor

The mesh convergence test was conducted by reducing the element size from 1.0 mm to 0.2 mm and it was observed that the reducing element size below 0.5 mm does not make a significant difference in peak stress. The element size of 0.5 mm with 600 elements in the PAAm hydrogel FEA model was considered mesh independent. Tactilus® pressure-sensing insole (Sensor Products Inc., 300 Madison® Ave STE 100, Madison, NJ 07940, United States) and the Tactilus® 4.1 software were used for reading the pressure values in the validation of the finite element model.

3. RESULTS AND DISCUSSION

The experimental results showed the PAAm hydrogel as hyper-viscoelastic. A similar model was used by Külcü (2019) and Lei et al. (2010). Figure 3(b) shows the FEA model for vertical stress variation for a 5.0 mm PAAm hydrogel sample.

The stress vs time curves of the FEA model and pressure insole results overlap each other showing the validity of the FEA model (Figure 3(c)). The expected stress of below 200 kPa can be achieved when the thickness of the PAAm hydrogel sample was above 6 mm under a constant force of 200 N. The uneven variation of pressure reduction (Table 1) could be due to friction acting at the bottom surface and the effect of barrelling of the sample. Significant reduction in peak pressure can be observed up to 8 mm (Figure 3(d)). The thickness increase beyond 8 mm does not reduce peak pressure significantly (Table 1) and may cause imbalance in the foot. An increase in thickness from 5 mm to 10 mm in steps of 1 mm results in a reduction in peak pressure by 6.3%, 5.2%, 7.1%, 1.8%, and 4.2% respectively compared to the predecessor sample (Table 1).

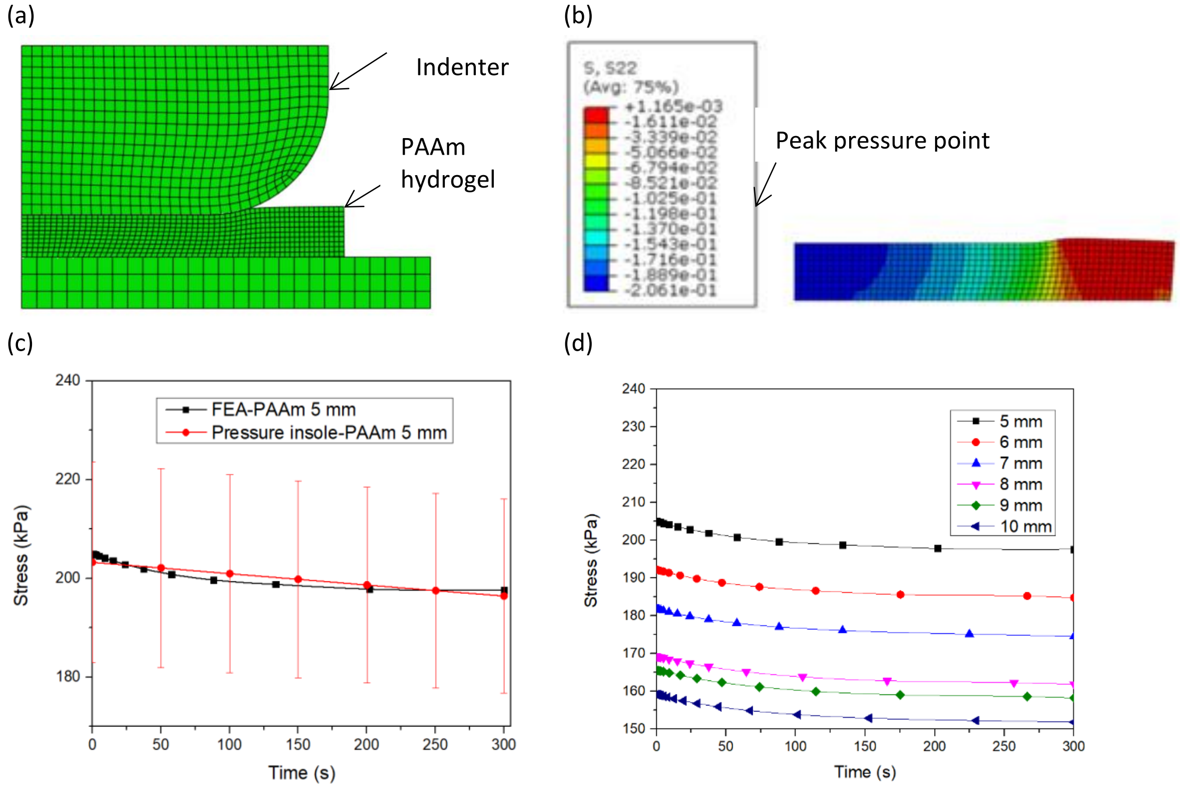

Figure 3: (a) FEA model to simulate pressure insole test arrangement. (b) FEA vertical pressure distribution for 5 mm thickness sample. (c) Comparison of peak pressure variation with time for FEA model and pressure insole. (d) Variation of stress with time for different thicknesses of hydrogels.

Table 1: Thickness and peak pressure values from the FEA model

Thickness (mm)	Peak pressure (kPa)	Percentage reduction (%)
5	205	-
6	192	6.3
7	182	5.2
8	169	7.1
9	166	1.8
10	159	4.2

4. CONCLUSION

The developed hyper-viscoelastic finite element model for PAAm hydrogel complies with pressure insole test results. The finite element results showed that the peak pressure reduction can be observed with the increase in thickness. The 5 mm to 10 mm thickness PAAm hydrogel modelled in Abaqus® finite element software showed that peak pressure reduction below 200 kPa can be observed above 6 mm thickness. The recommended thickness of PAAm hydrogel was 6 to 8 mm for an effective pressure distribution. A significant stress reduction cannot be obtained by increasing beyond this thickness range. imbalances on foot and an increase in the cost of material were other limiting factors that are to be considered when increasing the thickness. The significance of this research finding are, the ability to use PAAm hydrogel insole with effective thickness, to distribute pressure under a foot that needs a significant amount of peak pressure reduction such as diabetic foot ulcers.

ACKNOWLEDGEMENT

This research was supported by the NSF of Sri Lanka (RPHS/2016/DTM02), SRC (Senate Research Committee) University of Moratuwa (SRC/TP/2017/04), and Center for Biomedical Innovation (CEBI), University of Moratuwa. The pressure insole reading acquisition and processing were supported by Ms. Chathurani Dias, Research Engineer, CEBI, University of Moratuwa.

REFERENCES

Abaqus. (2014). ABAQUS User's Manual, Version 6.14. Dassault Systems Simulia Corp, Providence, RI.

Briody, C., Duignan, B., Jerrams, S., Tiernan, J. (2012). The implementation of a visco-hyperelastic numerical material model for simulating the behaviour of polymer foam materials. Computational Materials Science, 64, pp.47-51.

Castro, A. P., Yao, J., Battisti, T., Lacroix, D. (2018). Poroelastic Modeling of Highly Hydrated Collagen Hydrogels: Experimental Results vs. Numerical Simulation With Custom and Commercial Finite Element Solvers. Frontiers in Bioengineering and Biotechnology, 6.

Chen, W. P., Ju, C. W., Tang, F. T. (2003). Effects of total contact insoles on the plantar stress redistribution: a finite element analysis. Clinical biomechanics, 18(6), pp.S17–S24.

Cheung, J., Zhang, M. (2005). A 3-dimensional finite element model of the human foot and ankle for insole design. Archives of Physical Medicine and Rehabilitation, 86(2), pp.353-358.

Fernández-Seguín, L., Diaz Mancha, J., Sánchez Rodríguez, R., Escamilla Martínez, E., Gómez Martín, B., Ramos Ortega, J. (2014). Comparison of plantar pressures and contact area between normal and cavus foot. Gait & Posture, 39(2), pp.789-792.

Ghorbanoghli, A., Narooei, K. (2019). A new hyper-viscoelastic model for investigating rate dependent mechanical behavior of dual cross link self-healing hydrogel. International Journal of Mechanical Sciences, 159, pp.278-286.

Goske, S., Erdemir, A., Petre, M., Budhabhatti, S., Cavanagh, P. (2006). Reduction of plantar heel pressures: Insole design using finite element analysis. Journal of Biomechanics, 39(13), pp.2363-2370.

Iwgdfguidelines.org. (2021). [online] Available at: <https://iwgdfguidelines.org/wp-content/uploads/2021/03/IWGDF-2019-final.pdf> [Accessed 23 July 2021].

Külcü, I. (2019). Characterization of stress softening and self-healing in a double network hydrogel. Results in Physics, 12, pp.1826-1833.

Lei, J., Xu, S., Li, Z., Liu, Z. (2010). Study on Large Deformation Behavior of Polyacrylamide Hydrogel Using Dissipative Particle Dynamics. Frontiers in Chemistry, 8.

Lemmon, D., Shiang, T., Hashmi, A., Ulbrecht, J., Cavanagh, P. (1997). The effect of insoles in therapeutic footwear—A finite element approach. Journal of Biomechanics, 30(6), pp.615-620.

Martinez-Santos, A., Preece, S., Nester, C. (2019). Evaluation of orthotic insoles for people with diabetes who are at-risk of first ulceration. Journal of Foot and Ankle Research, 12(1).

Ogden, R. W. (1972). Large Deformation Isotropic Elasticity: On the Correlation of Theory and Experiment for Compressible Rubberlike Solids. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 328(1575), pp.567-583.

Silva, P., Crozier, S., Veidt, M., Pearcy, M. (2005). An experimental and finite element poroelastic creep response analysis of an intervertebral hydrogel disc model in axial compression. Journal of Materials Science: Materials in Medicine, 16(7), pp.663-669.

Udayanandana, R., Gunasekara, T., Silva, P. (2019). Compression Fatigue and Stress Relaxation Properties of Single Network Polyacrylamide Hydrogels. In: Moratuwa Engineering Research Conference (MERCon). [online] Colombo: IEEE, pp.533-537. Available at: <https://ieeexplore.ieee.org/document/8818924> [Accessed 21 July 2021].

Yavuz, M., Ersen, A., Hartos, J., Schwarz, B., Garrett, A., Lavery, L., Wukich, D., Adams, L. (2016). Plantar Shear Stress in Individuals With a History of Diabetic Foot Ulcer: An Emerging Predictive Marker for Foot Ulceration. Diabetes Care, 40(2), pp.e14-e15.