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CHARACTERISATION, MATERIAL MODELLING AND SIMULATION OF FLEXIBLE POLYURETHANE FOAM

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ABSTRACT:
Flexible polyurethane foam is an open-celled polymeric material that exhibits strain rate and temperature effects. It has found various applications in areas including the packaging, medical, sports, aerospace and aeronautical industries. Polyurethane foam is ubiquitous in seating applications and finds particular use in specialised wheelchair seating where customised seating solutions are required which can provide proper comfort and support without the risk of developing pressure ulcers. Proper seating design is critical for users if this problem is to be avoided, but a lack of quantitative knowledge of this material's behaviour has limited its effectiveness. The objectives of the work presented here are twofold. Firstly to characterise the behaviour of the materials and secondly to develop a validated numerical model which can be used to increase understanding of in-service behaviour.
Three commonly used foams having different densities and viscoelastic properties were subjected to compression in a uni-axial test machine fitted with a custom-built temperature chamber. The results of these tests were analysed and are presented to aid in the characterisation of these materials. The effects on the stiffness of foam of different additives, densities, strain rates and temperatures were noted.
A material model was developed to simulate indentation, in which compression and shear were the predominant modes of deformation. The results from the uni-axial characterisation tests were employed to determine material constants for Ogden's constitutive model for compressible materials. Simple shear tests were also conducted with a custom-built dual lap shear tester and material constants were then determined for this mode of deformation. A curve-fit was developed which was a compromise between both modes of deformation to provide increased material model robustness. To validate the accuracy of the developed model, uni-axial indentation of standard polyurethane seating foam was then modelled using Finite Element (FE) code. Results show a high degree of accuracy.

Keywords: *Foam, Characterisation, Material Modelling, Simulation*

1. Introduction

Wheelchair users can develop pressure ulcers as a result of upper body weight being transmitted through the tissue beneath the bony prominences of the pelvis. This weight can often be transmitted over extended time periods due to the user's failure to shift weight, which may be caused by a Spinal Cord Injury (SCI) or some other physical or neurological disability. A pressure ulcer can be defined as a localised injury to the skin or underlying tissue, usually over a bony prominence, as a result of pressure, or pressure in combination with shear or friction [1]. Pressure ulcers have the potential to interfere with physical, psychological and social well being and cause serious pain and discomfort which drastically decreases quality of life [2, 3]. There are two types of pressure ulcers, superficial and Deep Tissue Injury (DTI). Upon application of bodyweight, high pressure radiates outwards from bony prominences called the Ischial Tuberosities which are located on the pelvis. This high pressure can cause the damage which is termed DTI [4].Superficial ulcers occur on the outer layers of the skin tissue and can lead to some of the complications listed above, although generally the extent of a superficial pressure sore is not as serious as a DTI. Improved understanding of the behaviour of the materials used in wheelchair seating can enable superior designs with improved pressure distribution. This will improve comfort and support and potentially reduce the onset of pressure ulcers.

Polyurethane foam is widely used in wheelchair seating solutions as its physical properties offer good pressure relief in most situations. Polyurethane foam is an open celled elastomeric polymer and its constituent elastomer, polyurethane rubber, can undergo large and reversible elastic deformations. This material is known to exhibit three regions of different stress-strain behaviour in simple uniaxial compression: (i) approximately linear behaviour for strains less than about 0.05 – this linear elasticity arises from the bending of the cell edges, (ii) a plateau region in which strain increases at constant or nearly constant stress up until a strain of roughly 0.6 – this plateau arises from elastic buckling of the cell edges and (iii) a densification of the collapsed cell edges causing the foam to act as its elastomeric constituent material would. In this final region, known as the densification region, the slope of the stress-strain curve increases exponentially with strain as the crushed foam's cell struts and vertices come into contact [5]. When the material reaches this level of compression, it is referred to as 'bottomed out' – increasing the possibility of discomfort. Viscoelastic materials can be defined as an intermediate combination of elastic solids and viscous liquids [6]. All polyurethane foams exhibit some degree of viscoelasticity [7], but those sold specifically as viscoelastic foams display significantly more viscoelasticity by comparison with standard foams. Viscoelastic polyurethane foam is widely used in clinical seating as it offers excellent comfort and support due to its enhanced polymeric properties which are dependent on time, temperature and strain rate. The work presented in this paper is part of an ongoing investigation into improvements in the protocols involved in prescribing viscoelastic polyurethane foams in wheelchair seating.

2. Material Testing

2.1 Materials tested

A range of polyurethane foams used widely in the wheelchair seating industry were tested. Sunmate Blue manufactured by Dynamic Systems Incorporation is a type of viscoelastic, open-celled polyurethane foam with a density of 80kg/m^3. Sunmate Grey, with a density of 90kg/m^3, is manufactured by the same company and is the fire resistant version of sunmate blue. Sunmate Grey foam has flame-resistant additives mixed with the foam's constituent elastomer during its manufacture. Kayfoam FS-40, manufactured by Kaymed, is elastomeric, open-celled polyurethane seating foam. Kayfoam had a density of 40kg/m^3.

2.2 Uni-axial compression testing

Uni-axial compression testing was carried out on the selected materials in accordance with '*ISO 3386: Polymeric materials, cellular flexible – Determination of stress-strain characteristic in compression'* [8]. The compression tests were performed on a Lloyd LR 30K materials testing machine which had a calibrated 3kN Lloyd instruments load cell attached as shown in Figure 1. Test sample dimensions of 150mm length by 150mm breadth by 50mm height were chosen. The height of 50mm was that preferred in the ISO 3386 standard. The 150mm length by 150mm breadth dimensions were chosen as they were above the minimum 2:1 length/breadth to thickness ratio specified in the standard. The test piece was inserted centrally between two horizontal platens. The top platen which compressed the samples was connected to the 3kN load cell. The bottom platen was height adjustable at its four corners; this ensured that both platens were parallel during compression. A 0.5N preload was applied to the test piece, and was retained on the test piece even when the specimen was fully decompressed. This ensured that the test piece would not become 'loose' on decompression during repeated test cycles. For the first test, the sample was compressed by 30% of its initial height at a strain rate of 5mm/min. At this maximum deflection of 30%, the peak load was reached; the peak load is referred to later in the results section. This cycle was repeated immediately three times and on the fourth compression cycle, load-deflection data was recorded. The initial 3 cycles applied to the virgin foam sample removed any Mullins effect [9]. After recording the load-deflection, the sample was decompressed. This test procedure was then repeated at strain rates of 50, 100, 250 and 500 mm/min. Compression tests were carried out on each of the Sunmate Blue, Sunmate Grey and KayFoam samples.

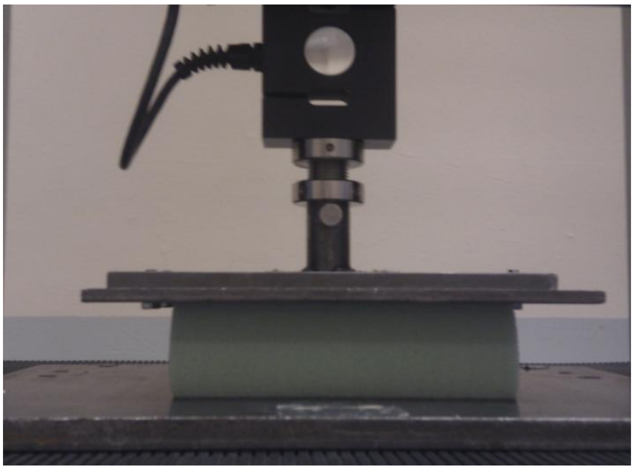
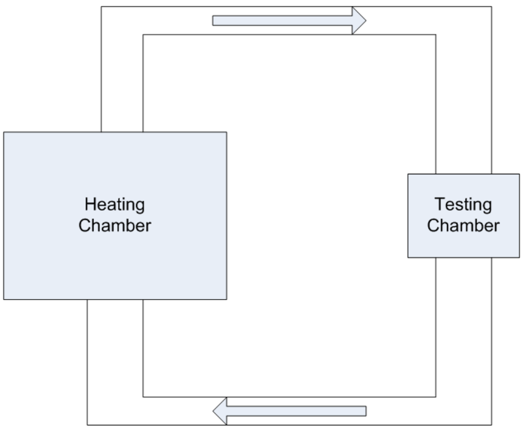


Fig.1: Uni-axial compression testing set-up

2.3 Temperature controlled uni-axial compression testing

Testing as described in section 2.2 was conducted on Sunmate Blue, Sunmate Grey and Kayfoam samples at temperatures of 25˚C, 30˚C and 37˚C. Raised temperature testing was conducted in a custom built and designed temperature controlled airflow system, the basic operation of which is described in the schematic Figure 2(a). Heated air which was produced by two 45W Pfaffenberg storage heaters in the external heating chamber was circulated around the system via two 0.5A axial fans. The compression testing was conducted in a test chamber which completely surrounded the test piece; the test chamber was designed to be easily disassembled to enable exchange of test samples (Figure 2(b)). The external heating chamber had a volume of 0.125m^3 which was 25 times larger than that of the testing chamber. This large volume ratio helped achieve accurate temperature control in the smaller volume testing chamber, as air temperature was stabilised in the larger volume external heating chamber before being circulated around the system. National Instruments (NI) equipment was used to monitor and control the system's temperatures during testing. The temperature in the system was monitored with temperature module NI-9211 and the system was controlled by the digital output module NI-9472. Both modules were mounted in the CompactRIO chassis control system. Foam, rubber or foil-backed foam insulation was applied to all external surfaces of the airflow system.

(a) 

(b) 

Fig.2: (a) Operational diagram of temperature controlled system; (b) Testing Chamber

2.4 Simple shear testing

Shear (rigidity) modulus testing was conducted in accordance with *'ISO 1827: Rubber, vulcanized or thermoplastic - Determination of modulus in shear'* [10]. A dual-lap testing rig, depicted in Figure 3, similar to that developed by Siriruk et al [11] for testing in simple shear, was designed and constructed. The foam parallelepipeds were identical and had the following dimensions: - 6mm thickness, 20mm width and 25 mm length. Sample size has a large effect on the shear modulus [12] and accordingly precaution was taken to ensure accurate sample size. Samples were bonded with cyanoacrylate adhesive on both sides to the rigid plates during testing. The shear load was applied at a rate of 4mm/min until sample failure. A minority of the shear tests failed at relatively low strain values due to adhesive failure - any test that failed at less than 100% shear strain was regarded as unrepresentative of material behaviour and that test's results were disregarded.

Fig.3 Shear test set-up, left hand side sample failed due to shear

2.5 Indentation Force Deflection testing

Indentation Force Deflection (IFD) tests [13] were conducted on the Sunmate Blue, Sunmate Grey and Kayfoam samples. A circular indenter based on *'ISO:2439, "Flexible Cellular Polymeric Materials--Determination of Hardness (Indentation Technique)'* but scaled down to 40.6 mm in diameter, to suit the 150mm length by 150mm breadth samples, was manufactured. This indenter was axially indented into the foam samples up to 65% of sample height using the Lloyd instruments testing machine. The result of this test is later presented and compared to the results suggested by a Finite Element (FE) simulation.

3. Presentation of results

3.1 Temperature dependence

Load-unload temperature compression testing was undertaken on Sunmate Blue viscoelastic polyurethane foam following procedures outlined in section 2.3. Experimental test results, not presented here, showed a high level of repeatability. Test results shown in Figure 4(a) indicate that the Sunmate Blue range viscoelastic foam had a large dependency on temperature. The decreasing area of hysteresis caused by the decreasing of the load curve in line with increasing temperature was notable. This was indicative of the Sunmate Blue foam sample softening as temperature increased. A reduction in peak load of 19.4% was recorded between 20°C and 37°C (Figure 4(d)). The same procedures were then undertaken on Sunmate Grey Fire Resistant viscoelastic foam (depicted in Figure 4(b)) and Kayfoam conventional polyurethane foam (Figure 4(c)). A reduction in peak compressive load of 10.5% was noted between 20°C and 37°C for the Sunmate Grey sample (Figure 4(d)). Over the same temperature range, a reduction in peak compressive load of 16.2% was recorded for the Kayfoam sample (Figure 4(d)).

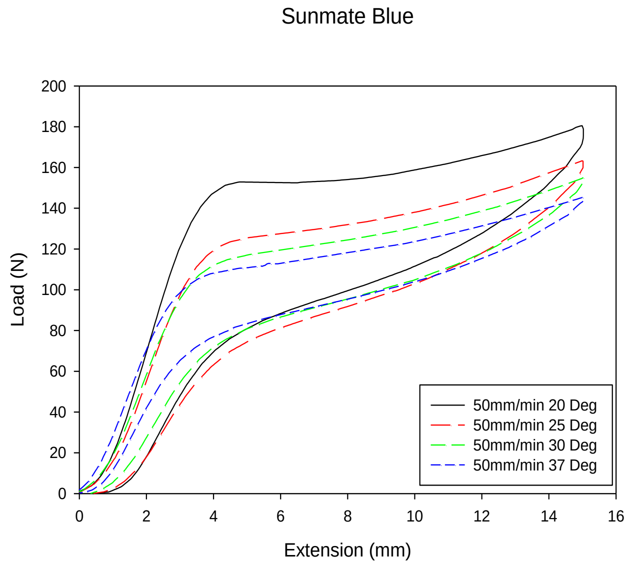


Fig. 4(a): Test results showing temperature dependence of viscoelastic foam sample

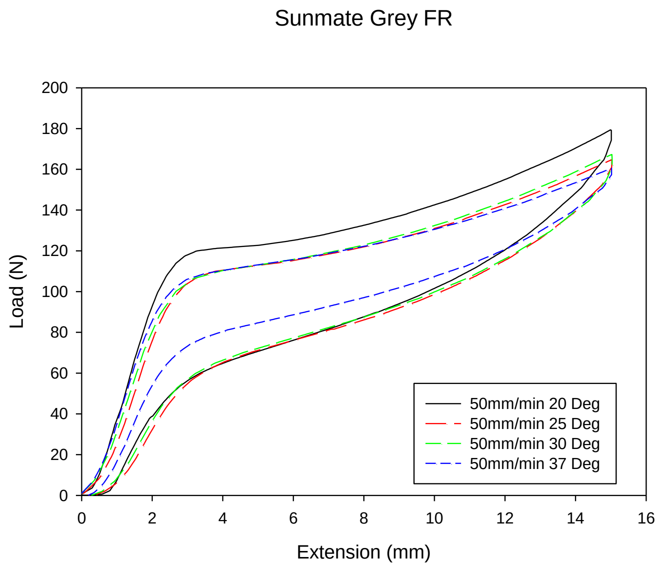


Fig. 4(b): Test results showing temperature dependence of Fire Resistant viscoelastic foam sample

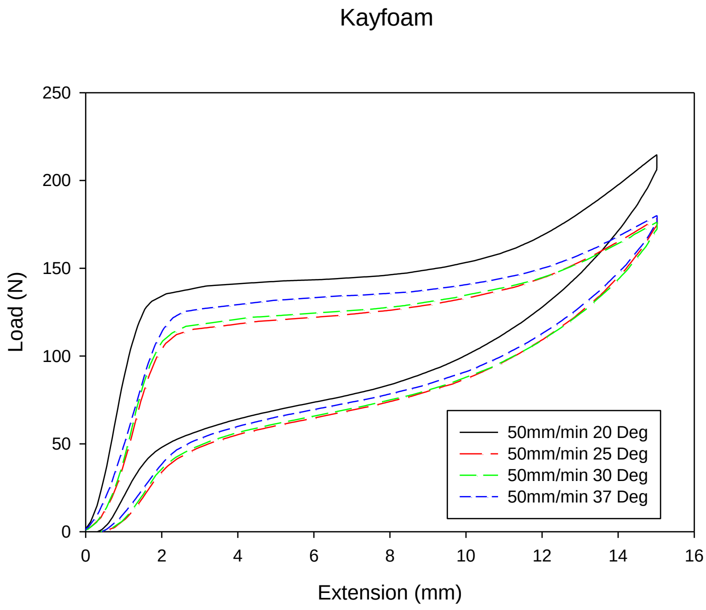


Fig. 4(c): Test results showing temperature dependency of conventional foam sample.

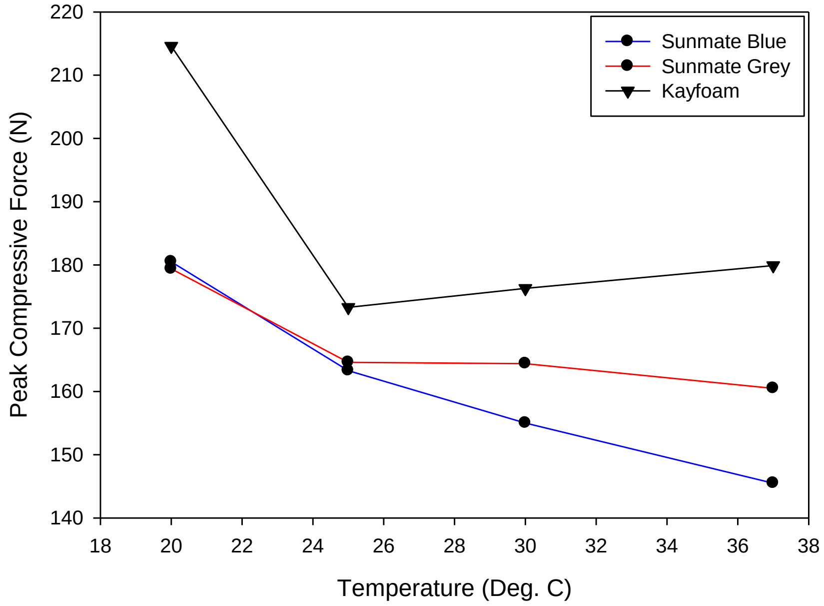


Fig. 4(d): Peak compressive loads at 15mm deflection for samples at different temperatures.

3.2 Rate dependence

Compression testing explained in section 2.2 was conducted on the three foam samples Sunmate Blue, Sunmate Grey and Kayfoam. The results from the strain rate tests on Sunmate Blue foam are displayed graphically in Figure 5(a). Sunmate Blue foam exhibited differences in load resulting from different strain rates. A reduction in maximum load of 29.6% was noted between the highest strain rate of 500mm/min and the lowest strain rate of 5mm/min.

For the same reduction in strain rate the peak load of the Sunmate Grey samples reduced by 33.2% (Figure 5(b)), which was a similiar reduction to the Sunmate Blue sample. The same test was conducted on Kayfoam (Figure 5(c)), with a reduction of 15.5% in peak load recorded from the highest to the lowest strain rates. Peak compressive loads for the three foam samples over the range of strain rates are displayed graphically in Figure 5 (d).

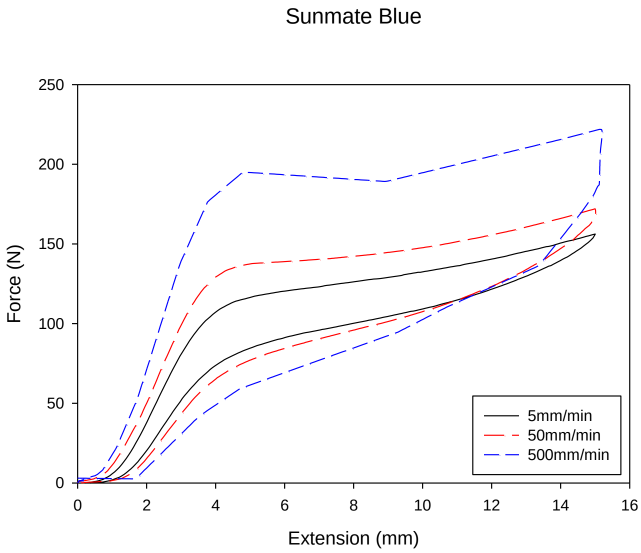


Fig. 5(a): Test results showing strain rate dependency of viscoelastic foam sample

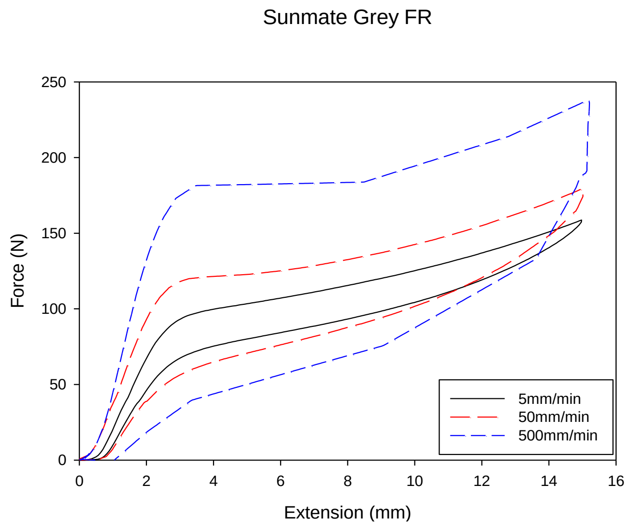


Fig. 5(b): Test results showing strain rate dependency of fire resistant viscoelastic foam sample

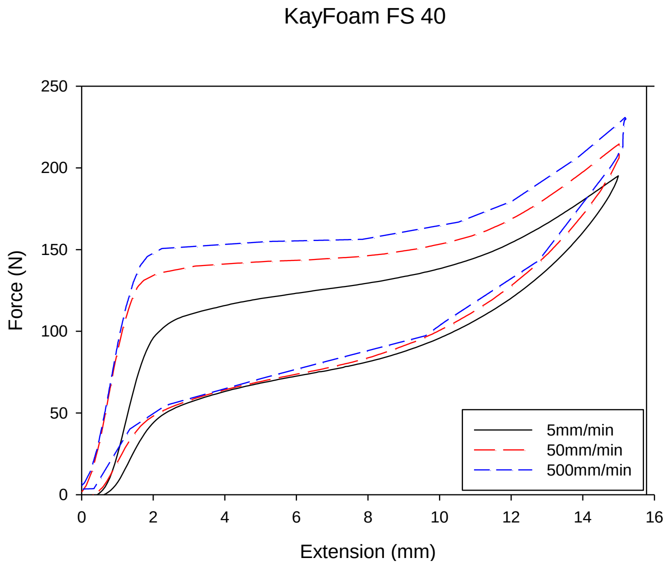


Fig. 5(c): Test results showing strain rate dependency of conventional foam sample

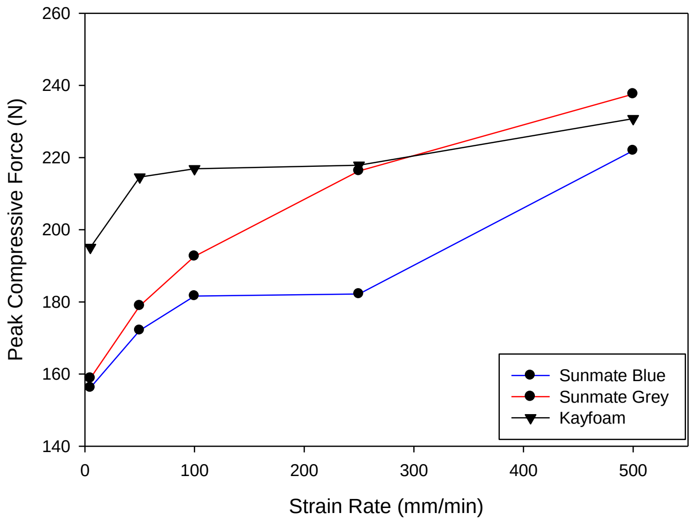


Fig. 5(d): Peak loads at 15mm displacement for different foam samples at different strain rates.

3.3 Higher strain results

Tests to a higher maximum strain were carried out on Sunmate Blue, Sunmate Grey and Kayfoam. The samples were compressed 80% of their initial height. The results of these tests are shown in Figure 6. The Sunmate Grey range of foam had a significantly higher stiffness at higher strains by comparison with the Sunmate Blue range of foams and the Kayfoam conventional foam (Table 1). The Sunmate Grey foam reached a peak which was 56.9% higher than the peak load of the Sunmate Blue range of foam.

	$Load_{80\%\ Deflection}$	Difference (%)
Sunmate Blue	928	N/A
Sunmate Grey	961.8	56.9
Kay-Foam	1455.9	3.6

Table 1: Peak loads at the higher deflection of 80%

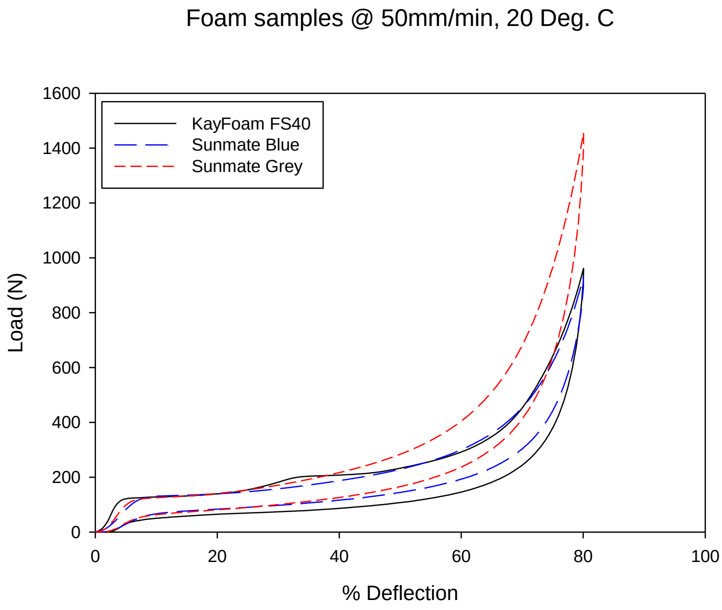


Fig. 6: Compressing samples to 20% of their initial height

3.4 Discussion of Results

3.4.1 Temperature dependence

Test results show some differences in performance between the Sunmate Blue and Sunmate Grey products. The Sunmate Blue foam softened proportionately over the full range of temperatures. The stiffness of the Sunmate Grey samples decreased between 20°C and 25°C. However between 25°C and 37°C there was a relatively small stiffness reduction for the Sunmate Grey sample. The overall stiffness reduction over the full range of temperature for the Sunmate Grey range was 10.5%; this was considerably less than that of the Sunmate Blue range at 19.4%. These results, presented graphically in Figure 4(d), indicated that the Sunmate Grey range of foam did not have the same temperature dependence as the Sunmate Blue range. The results of temperature controlled tests on Kayfoam conventional polyurethane foam indicated that the foam exhibited some viscoelastic effects as expected [7]. As the temperature was increased from 20°C to 25°C, a considerable reduction in stiffness was recorded. However once the temperature rose above 25°C, the recorded peak loads began to increase marginally. The overall reduction in stiffness for Kayfoam sample was recorded as 16.2%.

3.4.2 Strain rate dependence

Both the Sunmate foams showed a considerable dependence on strain rate, with similar reductions in stiffness experienced by both samples over the range of strain rates. These results indicate that both ranges of foam exhibited a similar degree of viscoelasticity. The Kayfoam conventional foam also displayed some rate dependent viscoelastic effects. However both the Sunmate Blue and Sunmate Grey viscoelastic foams displayed a significant reduction in peak load over the entire strain range, which at 29.6% and 33.2 % respectively was roughly double the 15.5% reduction in peak load experienced by the conventional Kayfoam.

3.4.3 Higher strain compression tests

Both the Kayfoam conventional foam and the Sunmate Blue viscoelastic foam samples had similar peak stresses when compressed by 80% of their initial height. The Sunmate Grey sample reached a much higher peak stress value, 56.9% higher than the Sunmate Blue sample. It is postulated that this higher stress arises from the stiffening effect of the inclusion of fire retardant particles in the physical composition of the foam [14].

4. Finite Element simulation of standard tests

Standard testing procedures on the Kayfoam conventional polyurethane foam sample were simulated using Abaqus CAE software [15]. Ogden's material model (Equation 1) for describing the behaviour of compressible rubber-like materials [16] was chosen as a suitable strain energy function.

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}.[\widehat{\lambda_1}^{\alpha_i} + \widehat{\lambda_2}^{\alpha_i} + \widehat{\lambda_3}^{\alpha_i} - 3 + \frac{1}{\beta_i}.\left(\left(J^{el}\right)^{-\alpha_i\beta_i} - 1\right)] \qquad (1)$$

Where λ_1, λ_2 and λ_3 are the principal stretches of the deformation, J^{el} is the elastic volume ratio, N is the order of fitting and μ_i, α_i, and β_i are temperature-dependent material parameters to be determined by curve-fitting material test data to the model. Uni-axial compression and simple shear material test data sets were fitted to the material model and material constants were extracted (Table 2) that gave the most accurate fit available. These coefficients were examined thoroughly as their accuracy was paramount to creating accurate simulations, their stability was ensured as they passed Drucker's stability criterion [15]. These modes of deformation were chosen as they were representative of the deformation undergone during seating. Only the loading curve was considered when evaluating the material parameters for the material model. Viscoelastic and hysteretic effects were not simulated in the model presented here.

N	μ (Pa)	α	β
1	12740.4	7.281	0
2	2.7459	-5.7311	0

Table 2: Coefficients of Ogden Hyperfoam model

4.1 Simulation of IFD testing

An IFD (Indentation Force Deflection) test [13] was conducted to demonstrate the accuracy of the material model. It can be seen from Figure 7(c) that the highest stress values were in tension along the side of the indenter. The stress values taken for the graph shown in Figure 8 were however an average of elemental stresses beneath the indenter. Good accuracy over the majority of the test, with some initial inconsistencies attributed to minor inaccuracies that were present in the material model that is described by the coefficients in Table 2 above. The models accuracy was also validated by visually comparing material deformation from tests and simulations at the sides of the sample and the grid deformation on the front face of the sample shown in Figure 7.

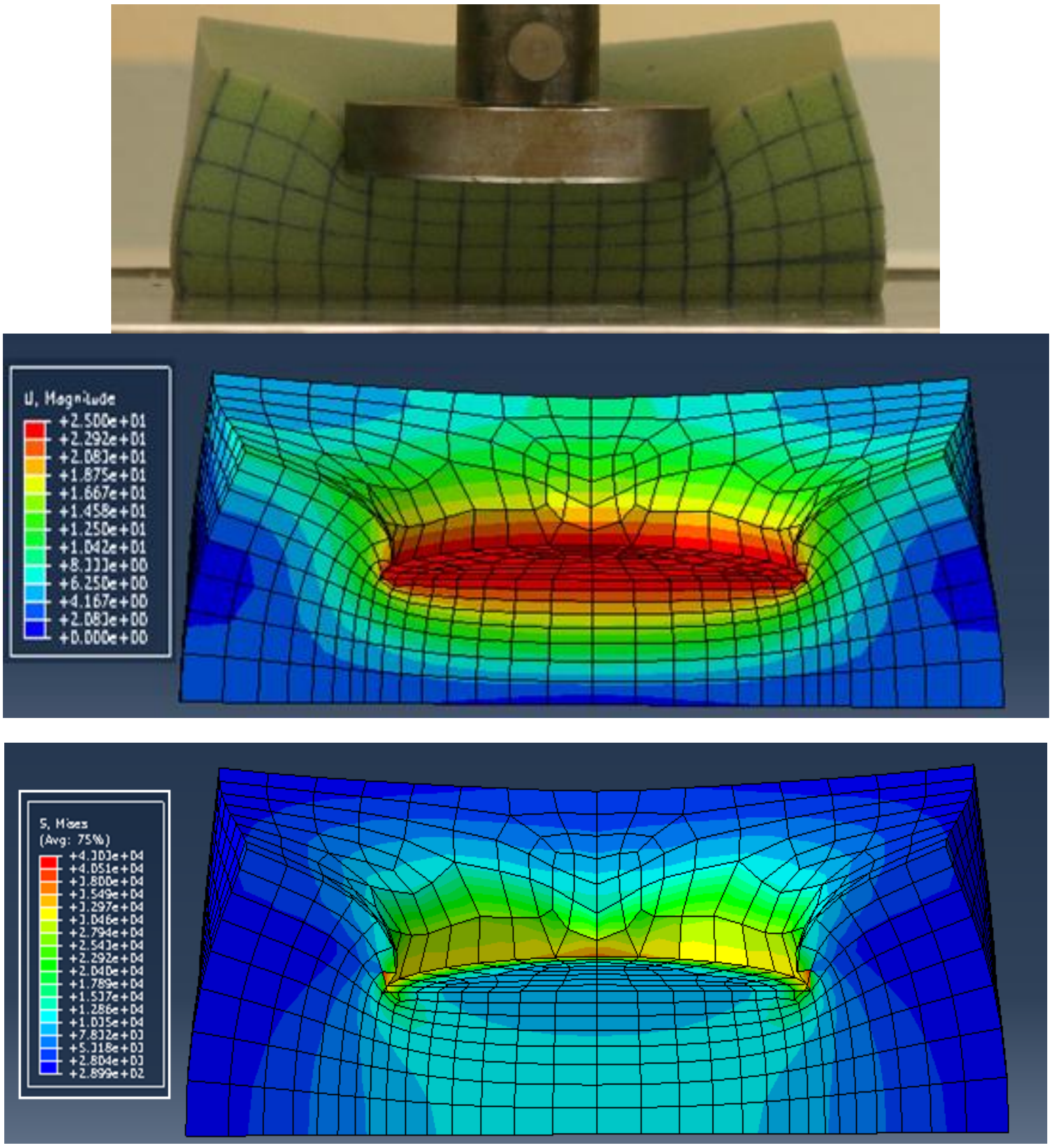


Fig.7 (a): IFD physical test set-up, ½ size sample compressed 50% of initial height; (b): Deformation plot of IFD test ½ size simulation in Abaqus compressed 50% of initial height (mm); (c): Von mises stress plot of IFD test ½ size simulation in Abaqus compressed 50% of initial height (Pa)

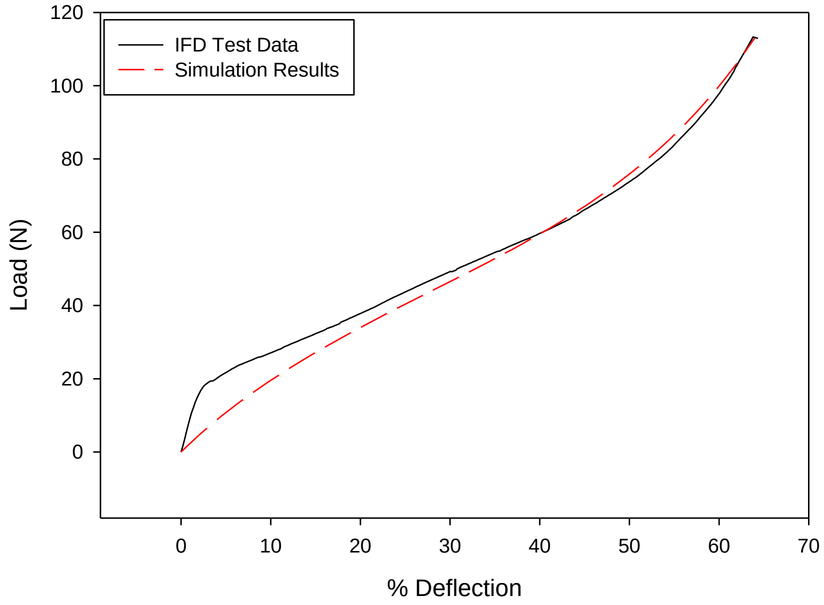


Fig.8: IFD test results compared to simulation results

5. Conclusions

Test results over a range of strain rates showed that all foam samples demonstrated some viscoelastic effects, but the two Sunmate products showed significantly greater viscoelastic effects than the standard foam, with the Sunmate Blue and Grey foams having similar load curves. Testing over a range of temperatures indicated that the Sunmate Blue product demonstrated a greater degree of softening at higher temperatures than either of the other products tested. Testing to high strains demonstrated that the sunmate grey foam shows a significantly higher stiffness in the densification region than either of the other two products. Future work related to this project concerns itself with the effects of raised temperature and high strains approaching densification on seating applications, and this work shows that the three commonly used foams exhibit significant differences in behaviour in conditions which would be expected in use as seating material.

A numerical material model was developed for one of these materials using the Ogden Hyperfoam model. A second-order model was created using uni-axial compression and simple shear data. This model was implemented in a simulation of an IFD test, and good correlation was found between test results and simulation.

Future work will include further material model development and verification, and the development and verification of temperature-dependent models to provide more realistic simulations of foam behaviour in wheelchair seating applications.

Acknowledgments

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