PROJECT REPORT – JOYCE FOAM

Evaluation of mechanical properties of a new foam material (Hygroflex foam) for medical mattress

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Abstract

The report examines the evaluation of a new foam material (known as Hygroflex) in relation to its mechanical properties compared to a number of existing foams. The primary aim was to evaluate Hygroflex foam in regard to pressure redistribution under body induced deformation. More specifically, it explores Hygroflex's pressure redistribution capacity for mitigation of pressure ulcer development due to long exposure to medical mattresses. The mechanical properties tested were those which play a vital role for use of foam in mattresses, especially medical mattresses used in hospitals. Five different variants of foam were subjected to different mechanical tests in order to evaluate their performance in relation to deformation and stiffness under simulant body part induced loadings. For example, loads exerted by a hip or ankle were replicated using simulant body parts, and the corresponding; deformation, contact development and pressure distribution around the respective simulant body parts were recorded. The properties of interests were; the peak pressure generated, pressure re-distribution over the immersed surface of the foam in contact with the simulant body part, and the immersion and wrap effects under body part induced deformation. The mechanical tests conducted were; a sharp indentation test, an envelopment test, a bulbous indentation test, shear tests, a roller arm test, and a cyclic test. A thermal test was also conducted to assess the heat dissipation ability of the various foams. The test results demonstrate that the newly developed Hygroflex foam has superior mechanical properties required in medical mattresses.

Keywords: Foam; Hygroflex; mattress; ulcer; pressure; pressure re-distribution; immersion; envelopment; pressure gradient

1 Background

The aim of the research project, jointly executed between RMIT University and Joyce Foam, was to study the properties of a newly developed foam material, Hygroflex, and whether it has potential to mitigate bed ulcer development. Hygroflex offers the features of memory foam combined with the functionality of high resilience foam. Hygroflex allows similar levels of immersion and envelopment as traditional memory foams, but has the recovery rate and cell characteristics of high resilience foams. This results in unique characteristics that could provide both vertical and horizontal stress reduction and lead to more uniformity in pressure distribution over the human body.

Several factors are thought to have an influence on pressure distribution and consequently on ulcer formation and its mitigation. Factors associated with ulcer formation are; pressure gradient, immersion, envelopment, duration of pressure, shear and friction, temperature control and moisture control. To address this, mechanical test procedures were established to evaluate the properties of the foam material that affect the pressure gradient on a body surface indenting or compressing into a foam material.

2 Tests

Several mechanical tests were developed to evaluate and compare the foam properties. Five variants of foam were subjected to these mechanical tests in order to evaluate their performance in relation to deformation and stiffness under simulant body part induced loadings. The mechanical tests conducted were; a sharp indentation test, an envelopment test, a bulbous indentation test, a shear test, a roller-arm test and a cyclic test. The purpose of the various mechanical tests was to evaluate the response of Hygroflex foam in relation to pressure gradient, duration of pressure, immersion, envelopment, and shear and friction, compared to four other variants of memory foams. A simple thermal test was also performed to assess the heat dissipation ability of Hygroflex foam.

2.1 Sharp Indentation Test

2.1.1 Aim

The aim of this test was to quantify the ability for each foam material to distribute pressure under a small, localised force, such as that exerted by a human heel.

2.1.2 Materials

A sharp shaped indenter with local indentation ability was used to replicate a standard human heel. The dimensions of the indenter were selected based on previous statistical studies on heel dimensions [1-4]. Previous literature found that the heel breadth is dependent on age [2, 4], height [3], gender [2, 4] and race [1]. Based on these studies, an average heal breadth of 60 mm was selected. The indenter was CNC routed at RMIT University, with a tolerance of 0.5 mm.

2.1.3 Methodology

The sharp indenter was used to compress a sample controlled by an Instron 5959 machine with a 10 kN load cell as schematically shown in Figure 2-1. The foam sample size was 200 x 200 x 100 mm. Two tests were performed; force control and displacement control. The indenter compressed the foam using either displacement or force control and was held at peak displacement or force for two minutes. A digital image correlation (DIC) technique was used to measure the distribution and peak strain around the indenter.

To quantitatively analyse the strain distribution, the strain was measured along two vectors of varying orientations. The strain was measured at six evenly spaced points along the vectors as shown in Figure 2-2. From the six strain measurements, a through-thickness strain distribution was calculated for all foams.

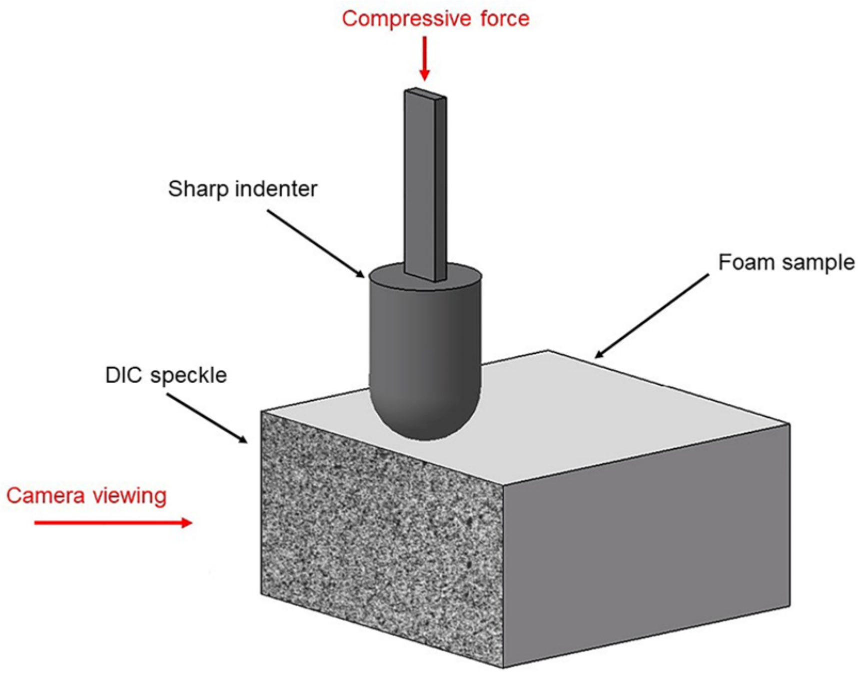


Figure 2-1: Schematic of sharp indenter test method.

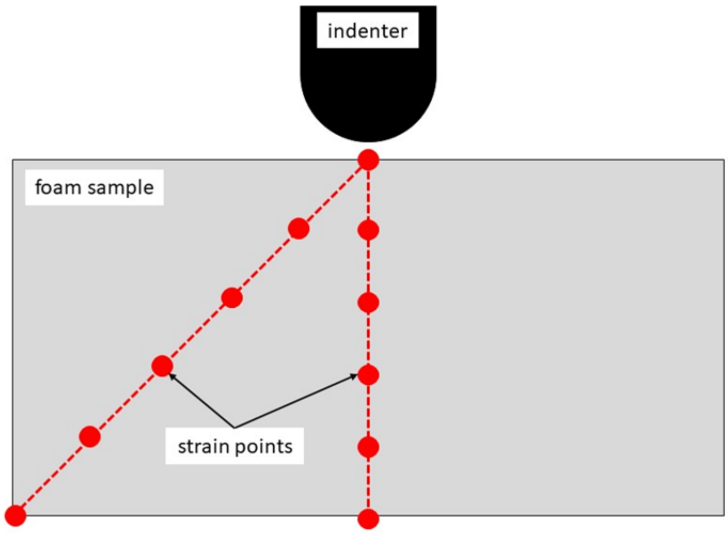


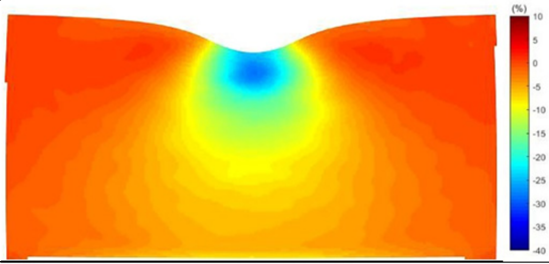
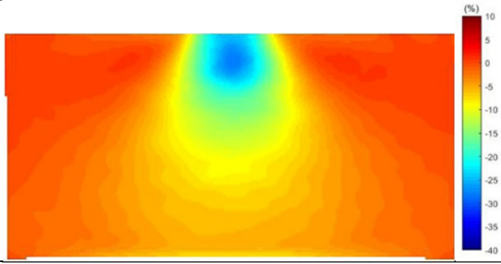
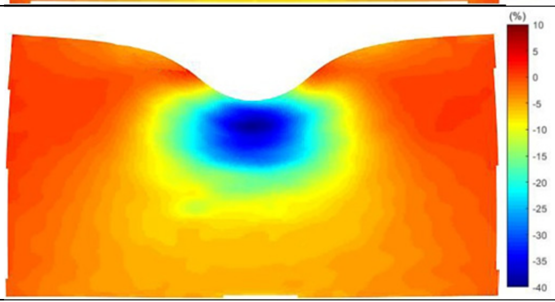
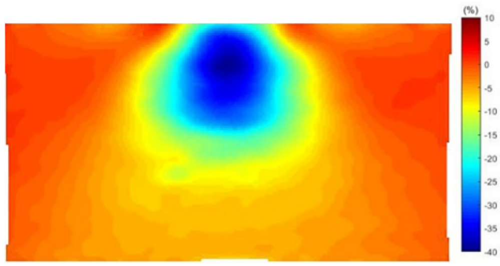
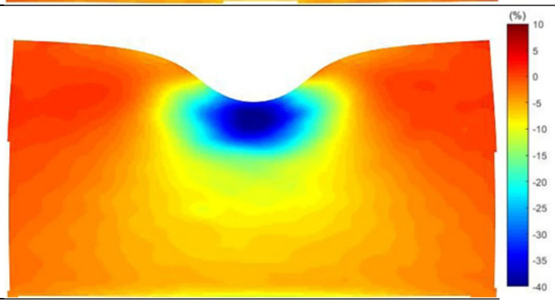
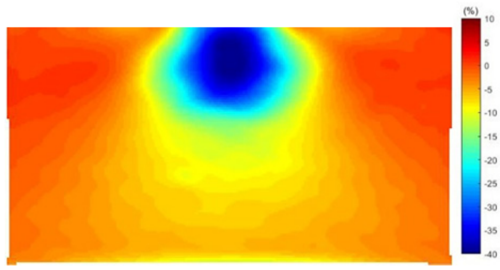
Figure 2-2: Schematic showing strain vectors through the thickness of foam.

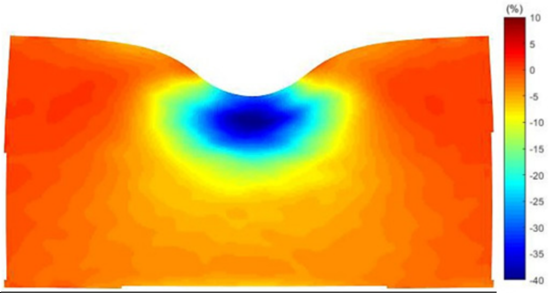
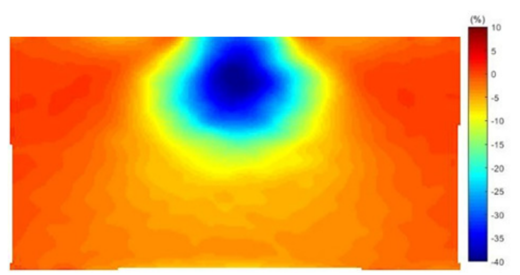
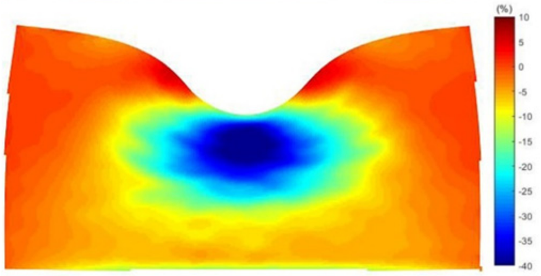
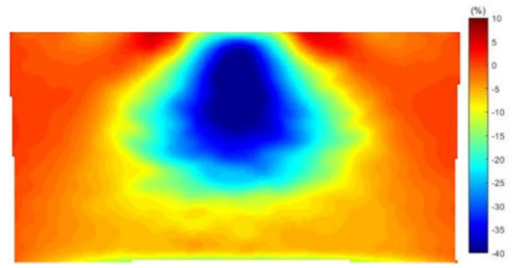
2.1.4 Results

2.1.4.1 Force control tests

During force control, the sharp indenter was compressed into the foam until the peak force reached a set value. In this case, the foam was compressed until the force transducer read 8 N. Once an 8 N force was recorded, the indenter was held in place for two minutes before strains were measured. This allowed the memory foams sufficient time to redistribute the pressure. The strain distributions for the various foams were compared in Table 1, which displays the deformed and undeformed transverse (vertical, in the direction of the indenter) strain fields for each foam sample after two minutes held at peak (8 N) load. The strain range (tensile – compressive) shown in Table 1 represents 10 % to - 40 % strain. The blue regions represent areas of high strain due to compression from the indenter. High strain represents a high magnitude of foam deformation.

Table 1: Longitudinal strain (ε_{yy}) maps different foam materials after two-minute hold at peak (8 N) force.

Material	Deformed	Undeformed
A		
B		
C		

D		
Hygroflex		

The strain field depicted in Table 1 represents the finite longitudinal strain (ε_{yy}) in the vertical direction for each foam sample (Foams A, B, C, D and Hygroflex) under an 8 N compressive load from the sharp indenter. Figure 2-3 indicates the fraction (percentage) of high-strain area (deemed within 15 to 40 % strain). The results were normalised against the foam with the greatest high-strain region (Hygroflex). The bars represent the fractions of high-strain regions generated in Foams A-D in comparison to Hygroflex foam.

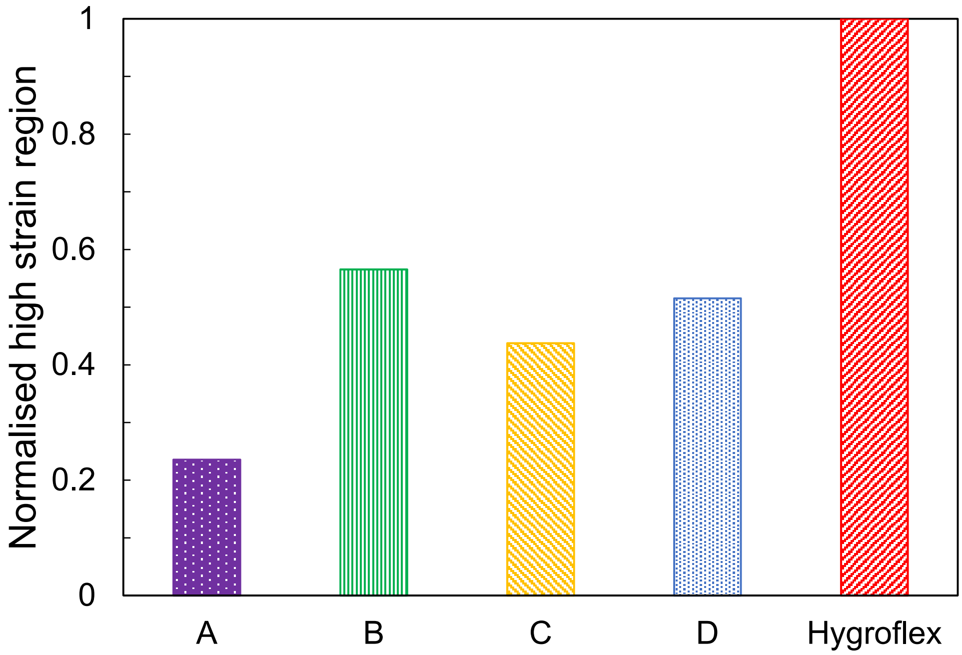
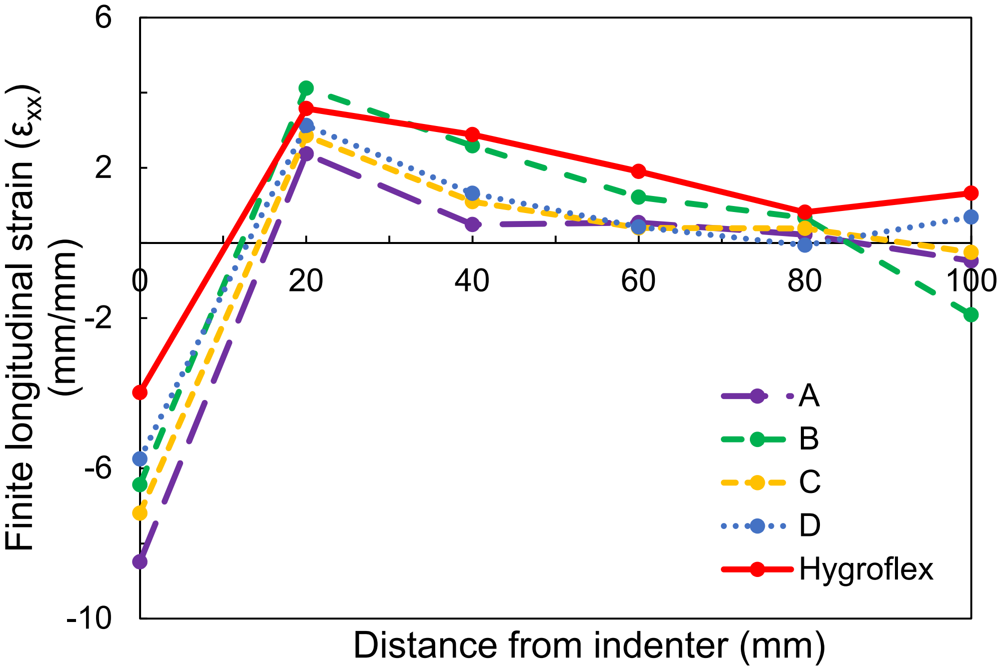
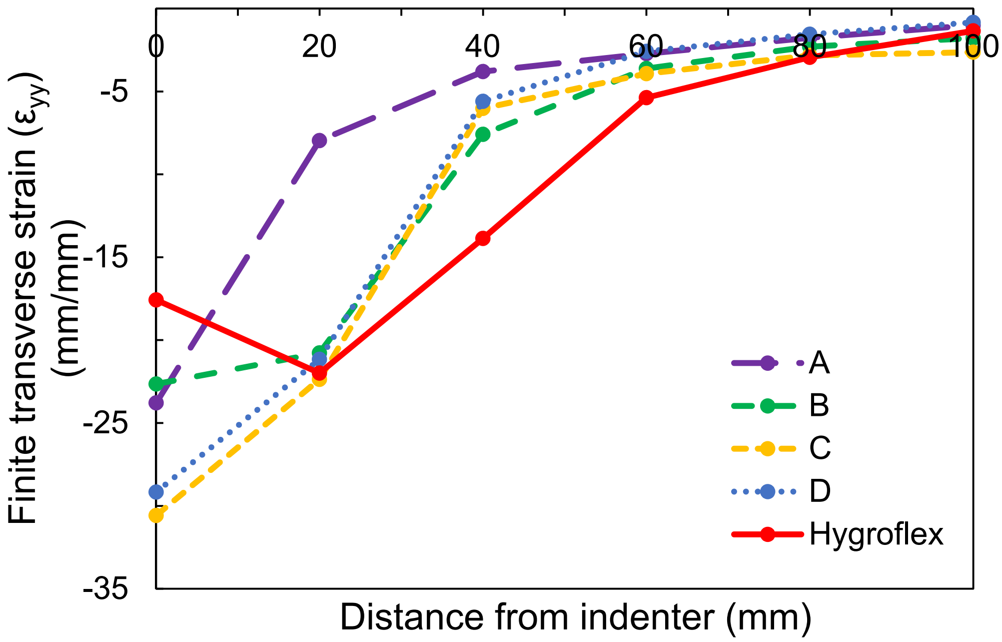


Figure 2-3: Normalised high-strain regions for all foams under an 8 N compressive force in the sharp indentation test.

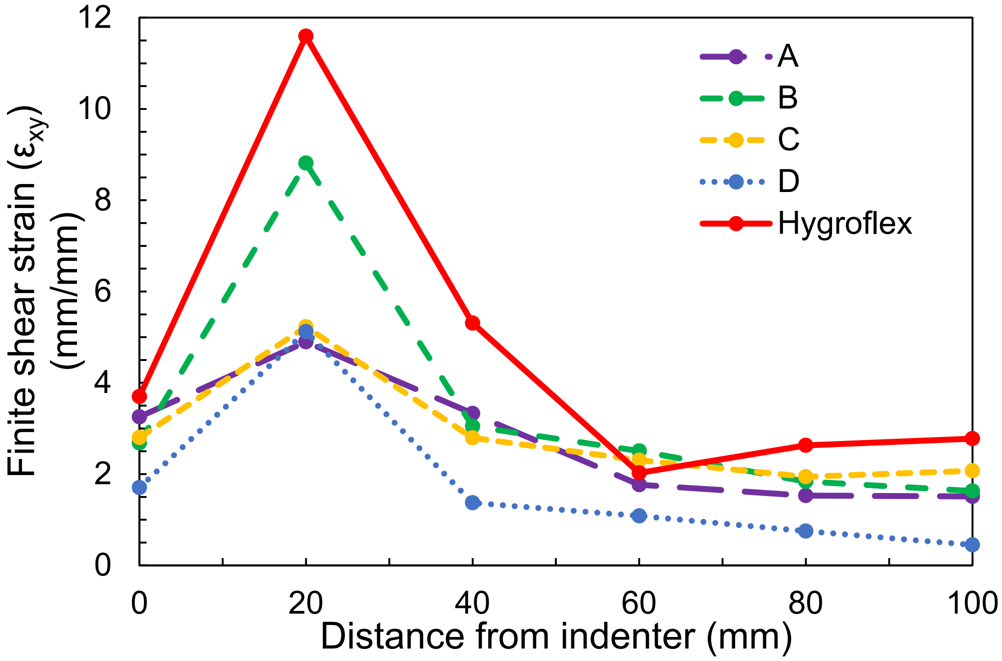
Under a fixed 8 N load applied to all foams, Hygroflex had the largest area of high-strain (15-40 %). The cell microstructure of Hygroflex enables it to deform uniformly and over a larger region compared to the other foams (~43 % more than the next foam type – Foam B). The through-thickness longitudinal (ε_{xx}), transverse (ε_{yy}) and shear strain (γ_{xy}) values were extracted at several points through the thickness of the foam sample to measure the strain field gradient. The results are presented in two sections. Figure 2-4 shows angled-line strain field results and Figure 2-5 shows the results for the straight-line strain fieldFigure 2-5.



(a)

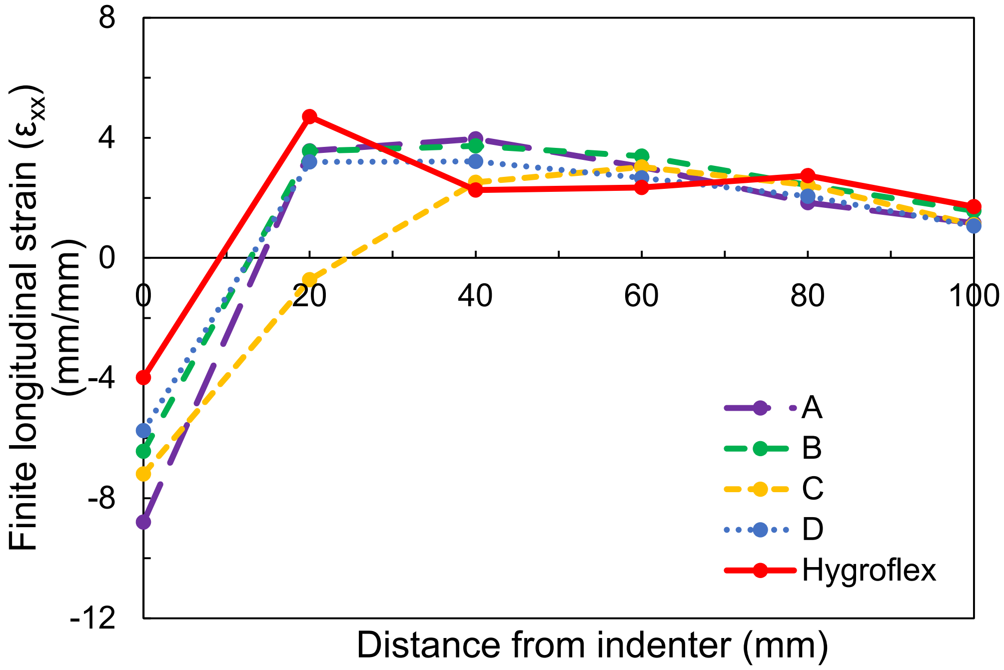


(b)



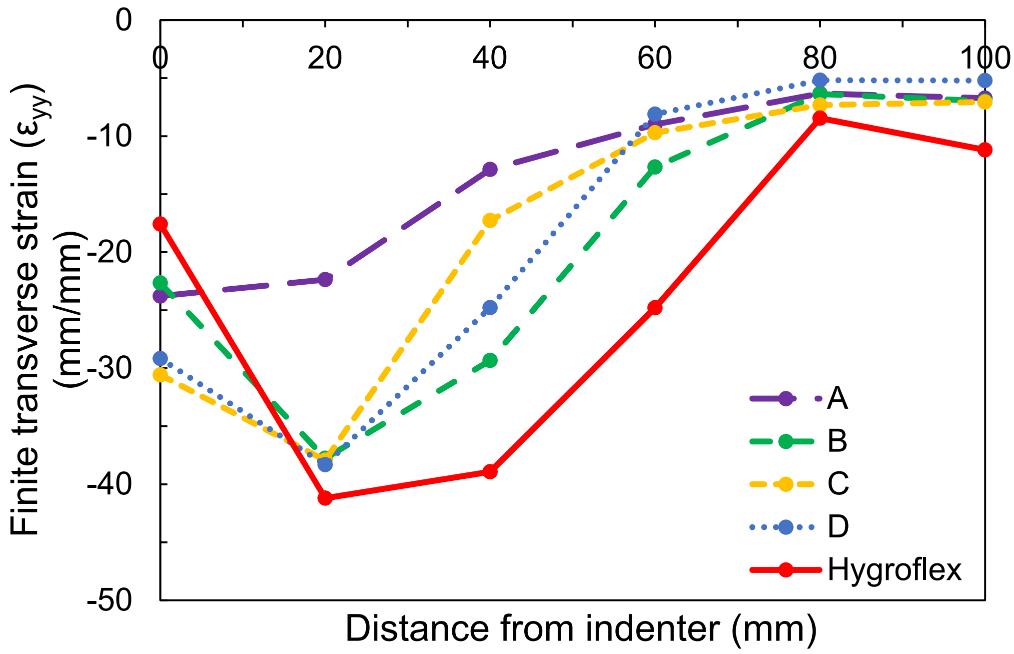
(c)

Figure 2-4: Force control (a) longitudinal (b) transverse and (c) shear strain values measured from directly under the indenter to the bottom left corner of the sample (angled line in Table 1).



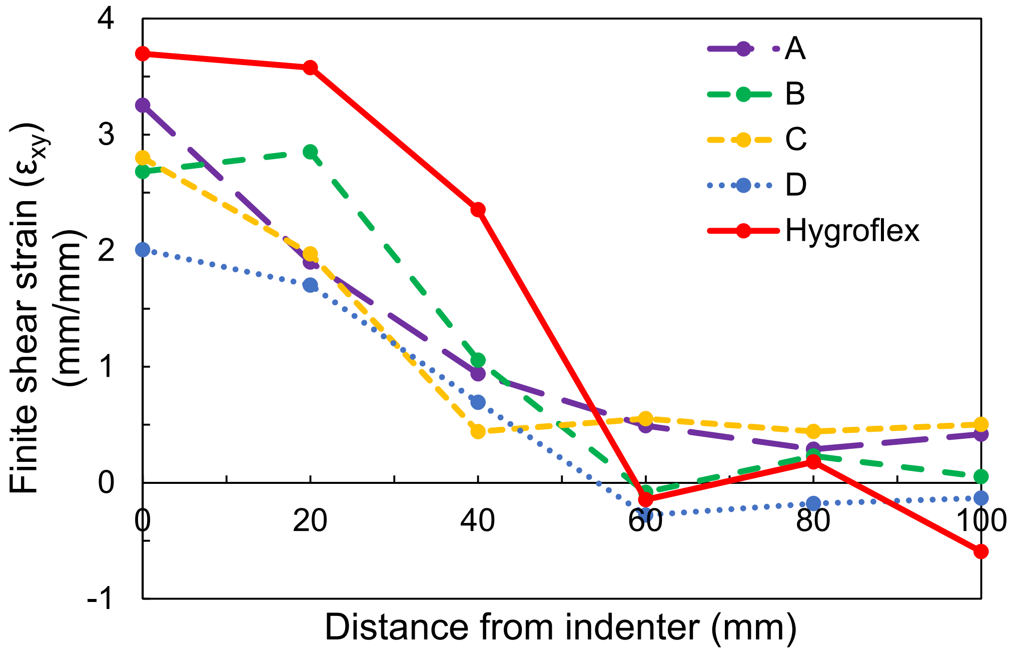
8
4
0
-4
-8
-12
0
20
40
60
80
100
Finite longitudinal strain (ε_{xx})
(mm/mm)
A
B
C
D
Hygroflex
Distance from indenter (mm)

(a)



0
-10
-20
-30
-40
-50
0
20
40
60
80
100
Finite transverse strain (ε_{yy})
(mm/mm)
A
B
C
D
Hygroflex
Distance from indenter (mm)

(b)



(c)

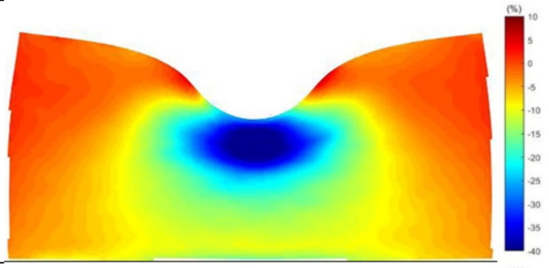
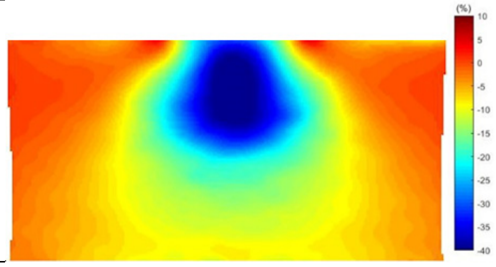
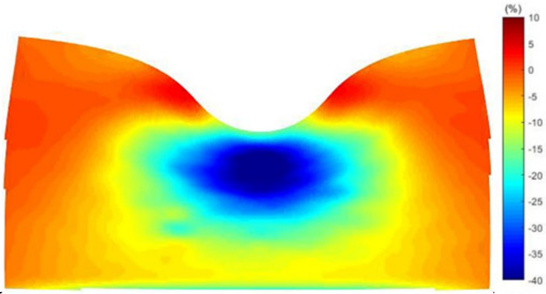
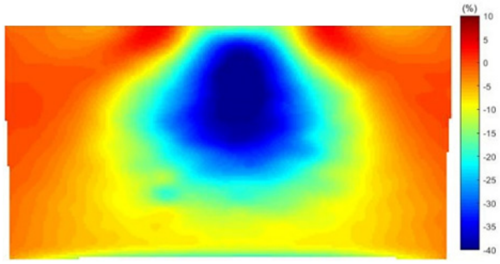
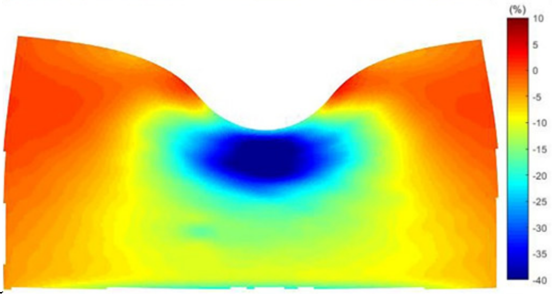
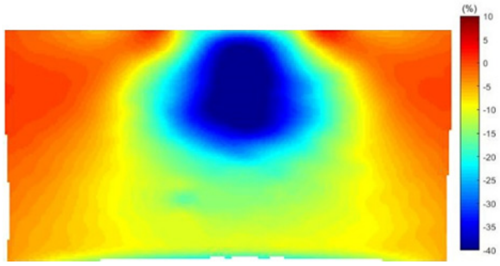
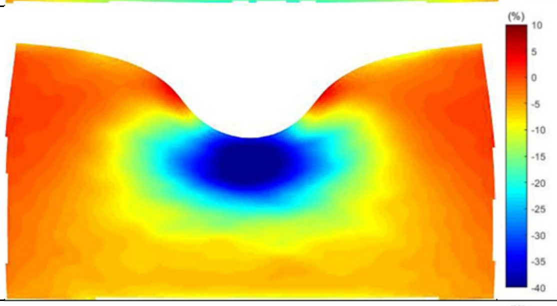
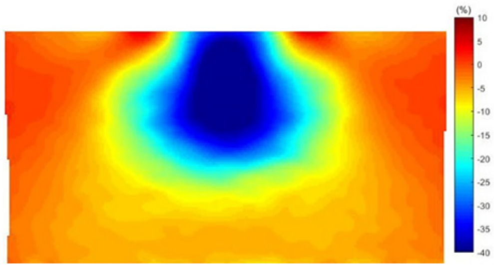
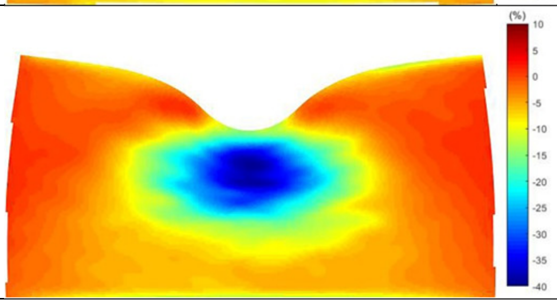
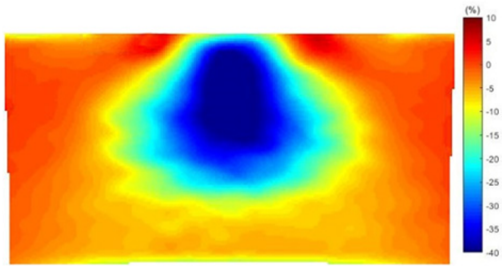
Figure 2-5: Force control (a) Longitudinal (b) transverse and (c) shear strain values measured from directly under the indenter to the bottom of the sample directly under the indenter (straight line in Table 1).

2.1.4.2 Displacement control

In displacement control, the sharp indenter was pressed into the foam until the sample was compressed by 40 % of its thickness. After compressing 40 mm of the 100 mm sample thickness, the indenter was held in place for two minutes to allow the memory foam deformation to reach a steady state before strain measurements were taken. Table 2 shows the deformed and undeformed transverse (i.e., vertical or in the direction of the indentation) strain fields of each foam sample after two minutes held at 40 % strain. As mentioned previously, the blue regions represent areas of high strain due to compression from the indenter. High strain refers to regions of the foam that are subject to large deformations. Foams with large high-strain regions have greater contact area with the indenter, which results in increased pressure redistribution.

Table 2: Longitudinal strain (ε_{yy}) maps of different foam materials after two-minute hold at peak (40 %) strain.

Material	Deformed	Undeformed

A		
B		
C		
D		
Hygroflex		

The strain field depicted in Table 2 represents the finite longitudinal strain (ε_{yy}) of each foam under 40 % compression from the sharp indenter. Figure 2-6 qualitatively highlights the fractional area of high-strain (15-40 %) in the foam. When compressed by 40 % of its initial thickness, the microstructure of Foam B was able to further deform than other foams (~15 % more than the next foam, Hygroflex)

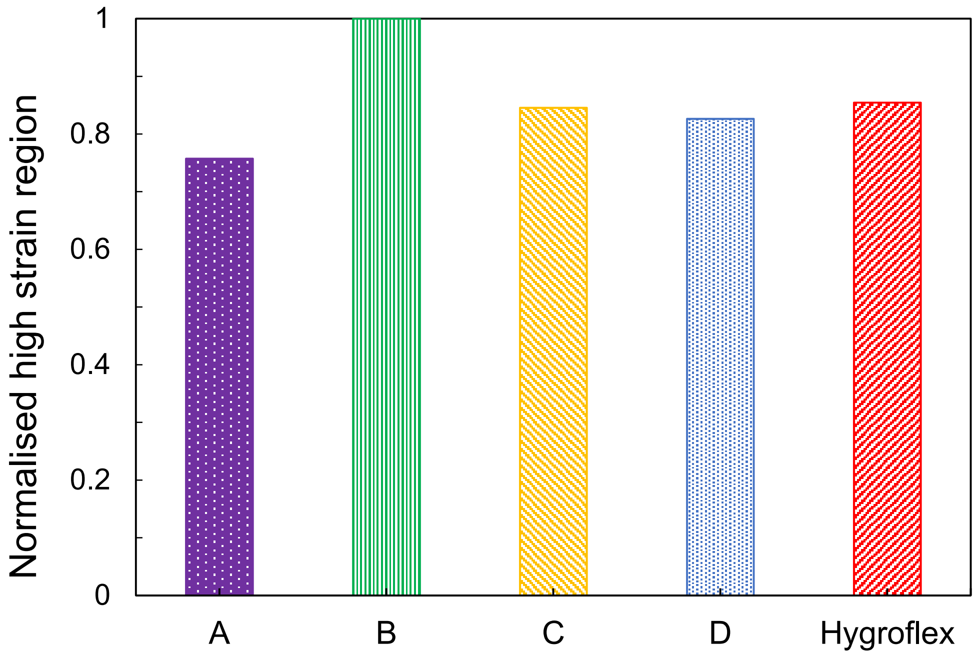
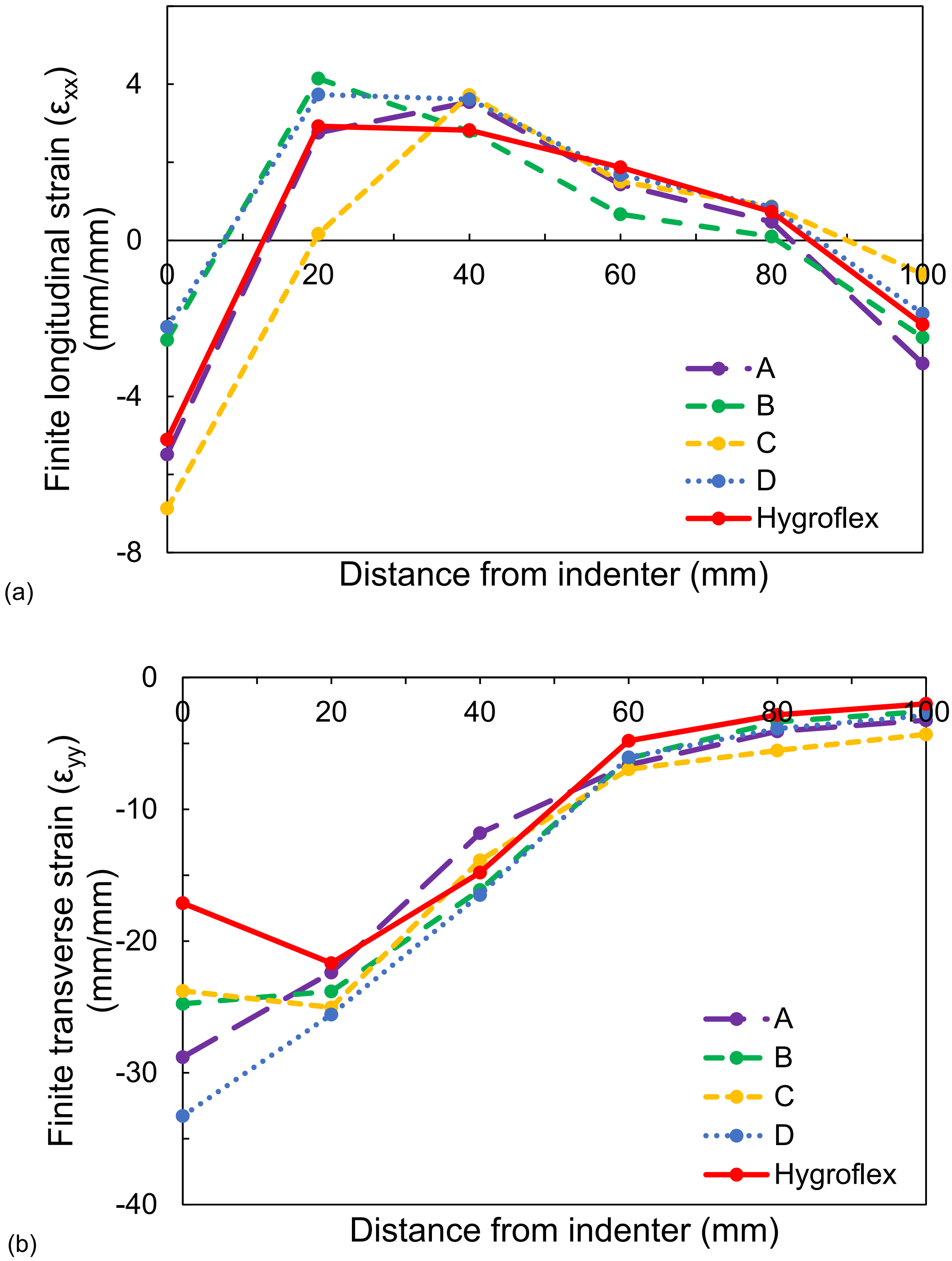
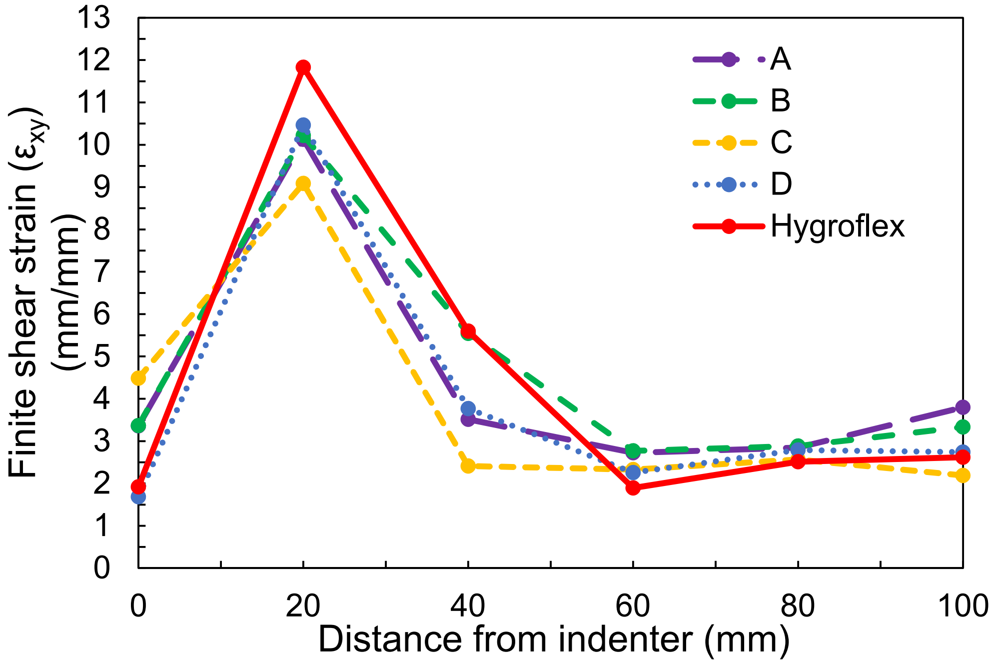


Figure 2-6: Normalised high-strain region for all foam materials under 40 % strain from sharp indenter.

The longitudinal (ε_{xx}), transverse (ε_{yy}) and shear strain (ε_{xy}) values were extracted at several points through the thickness of the foam to assess the strain field gradient. The results are presented in two sections. Figure 2-7 shows angled-line strain field results, and Figure 2-8 shows straight-line strain field results.

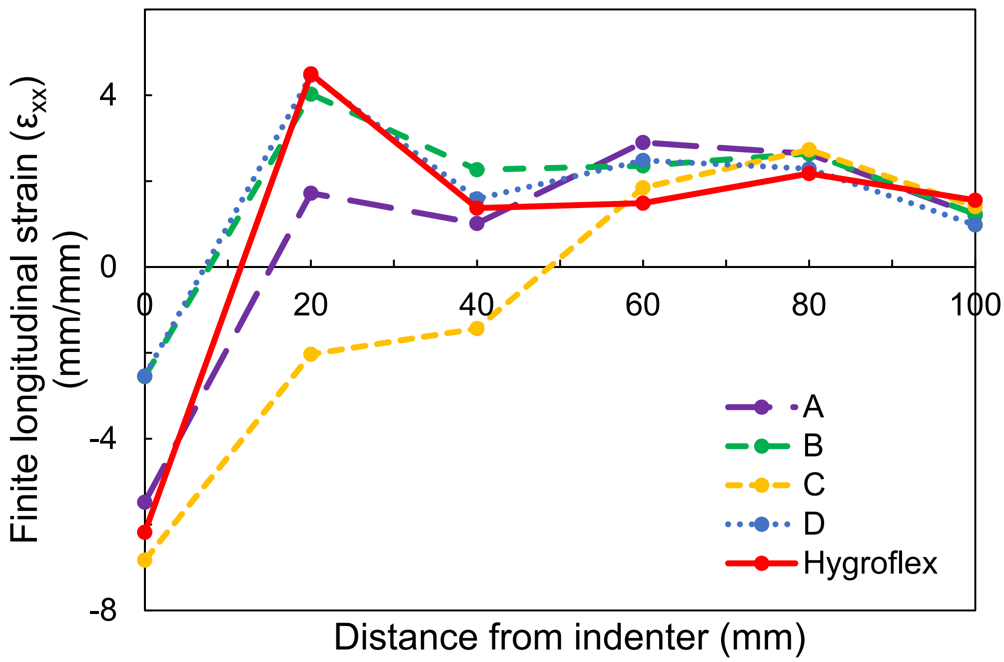


Finite longitudinal strain (ε_{xx}) (mm/mm)
4
0
-4
-8
0
20
40
60
80
100
A
B
C
D
Hygroflex
Distance from indenter (mm)
(a)
0
-10
-20
-30
-40
0
20
40
60
80
100
Finite transverse strain (ε_{yy}) (mm/mm)
A
B
C
D
Hygroflex
Distance from indenter (mm)
(b)

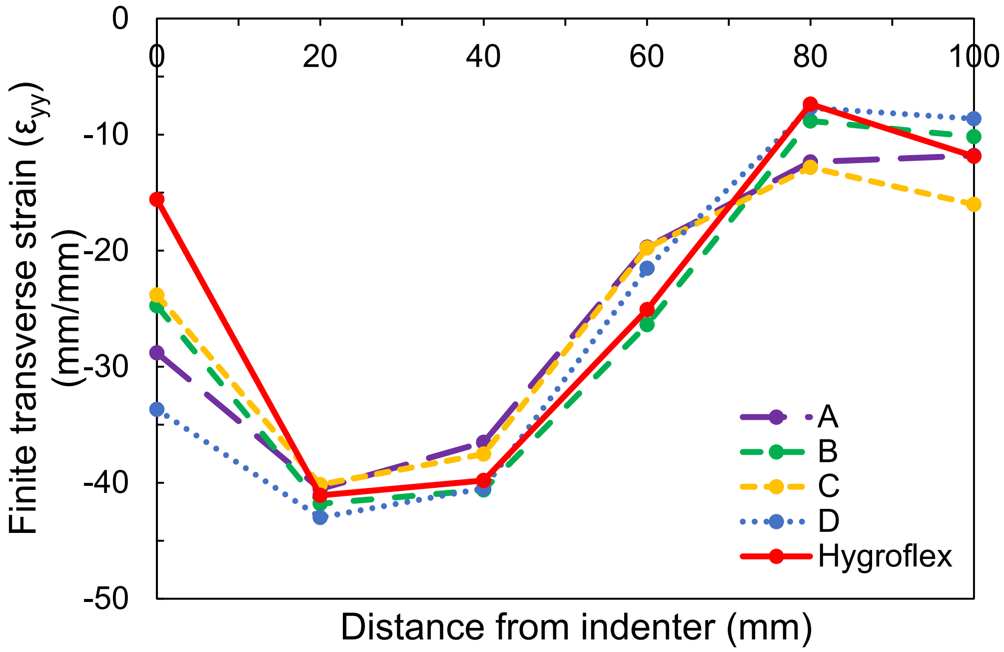


(c)

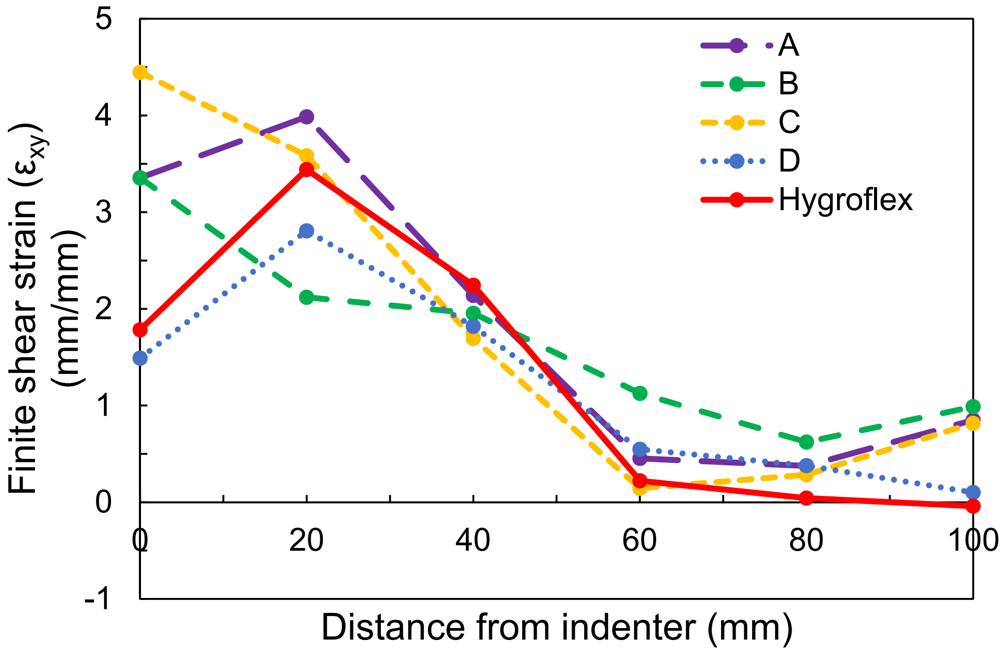
Figure 2-7: Displacement control (a) longitudinal (b) transverse and (c) shear strain values measured from directly under the indenter to the bottom left corner of the sample (angled line in Figure 2-2).



(a)



(b)



(c)

Figure 2-8: Displacement control (a) longitudinal (b) transverse and (c) shear strain values measured from directly under the indenter to the bottom of the sample directly under the indenter (straight line in Figure 2-2)

2.1.5 Implications for Medical Applications

It is impossible to remove pressure on the skin/body while using a matress, particularly at bony prominences. The main challenge with the use of support surfaces to minimise pressure induced ulcer formation is ensuring that the pressure is maintained at a ‘safe’ level or for a ‘safe’ amount of time. In general, this is achieved through pressure redistribution by ‘spreading the load’ over the body surface in contact. The efficient distribution (spreading) of the contact body force is described as envelopment or immersion [5].

Immersion refers to the sinking of the body into the support surface, resulting in a greater contact area. A greater contact area for a given force will result in a lower interface pressure (Pressure = Normal force/Area), thus reducing the potential of developing pressure ulcers. Immersion is usually measured by how far the body sinks into the support surface [6, 7].

However, in this study, immersion was measured by strain rather than displacement. Strain refers to the measure of deformation (movement of material from its original position) to an applied force. Side-on digital image correlation (DIC) was able to quantify the through-thickness strain. Under a fixed displacement, the high-strain region was similar for all the foams. However, under a fixed force, the high-strain region was greatest for Hygroflex. Likewise, the magnitude of largest strain under a fixed force was highest for Hygroflex. This shows that Hygroflex had the largest foam deformation around the indenter, which would result in a better redistribution of the interface pressure.

2.2 Envelopment Test

2.2.1 Rationale

The aim of the test was to compare the surface area of the impression left from representative human buttocks. This test evaluates the amount of envelopment around simulant human buttocks under different force conditions. Envelopment refers to how well the support surface conforms to the contours of the body.

2.2.2 Materials

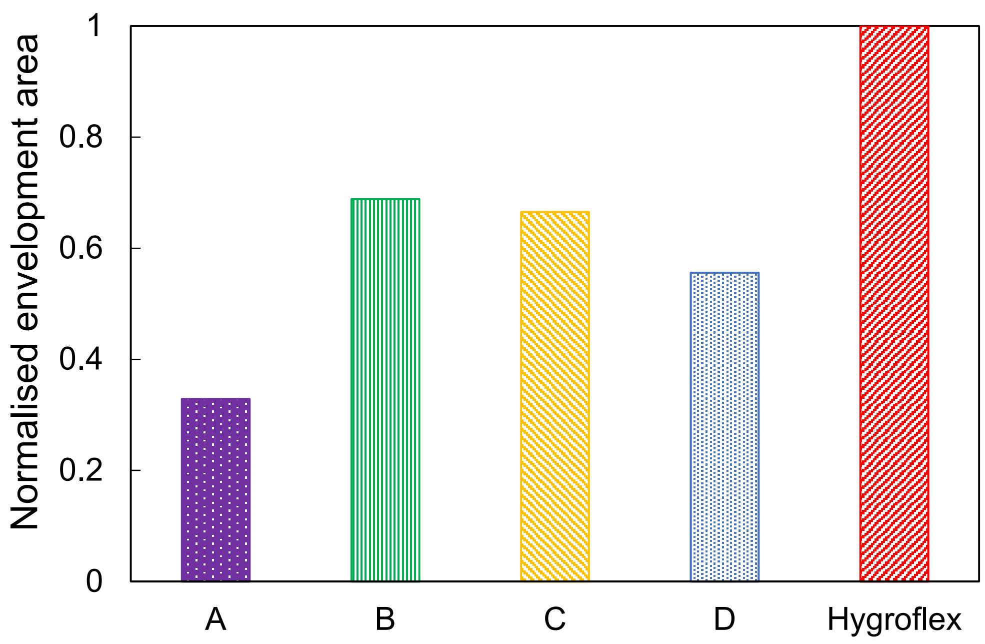
A bulbous shaped indenter was used to replicate standard (typical) human buttocks. The size, shape and dimensions of the indenter were selected based on standard buttock dimensions referenced in the International Organisation for Standardization (ISO) standard 16840 [8]. The indenter was CNC routed at RMIT University, with a tolerance of 0.5 mm. A black dye was used to enable imprinting of the buttock shape onto the foam surface.

2.2.3 Methodology

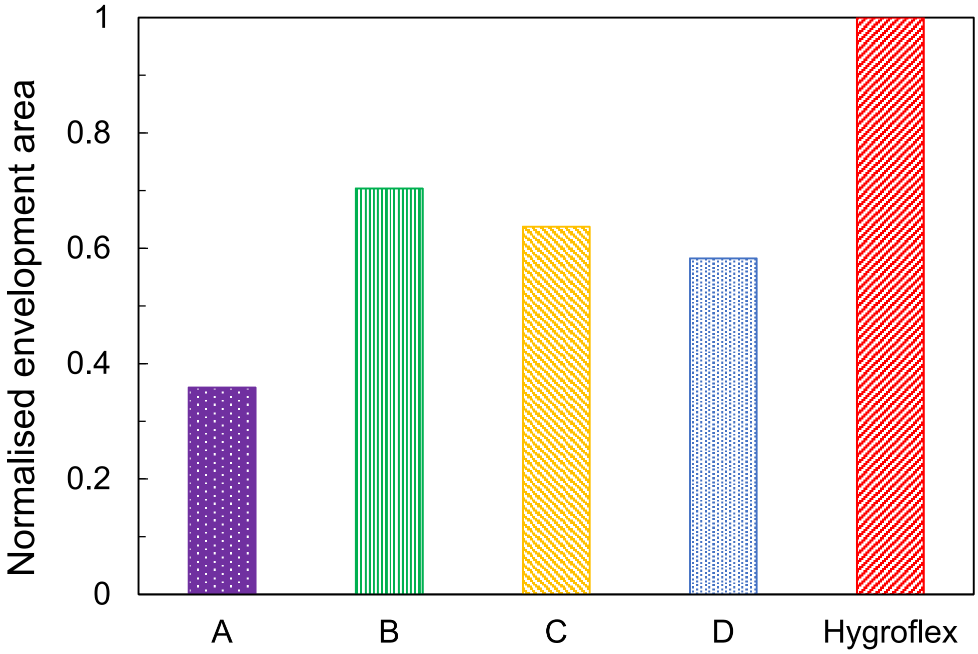
The bulbous shaped indenter was used to compress a 400 x 400 x 100 mm foam sample controlled by an Instron 5959 machine with a 10 kN load cell. A dye was applied to the surface of the indenter to measure the contact area on the foam. Two applied loads (50 N and 75 N) were used in this study to replicate two body sizes and weights. The percentage area was calculated using an image editor (Adobe Photoshop CC) and normalised against the foam with the largest envelopment area.

2.2.4 Results

Table 3 displays the indenter area in each of the foams under 50 N and 75 N loads. The respective areas for each of the foams under both load cases was normalised against that of Hygroflex. The normalised envelopment areas for all the foams under both 50 N and 75 N loads are displayed in Figure 2-9. The results show that under both loads (50 N or 75 N), Hygroflex had the greatest envelopment area. Under a 50 N load, Hygroflex had a 67, 31, 33 and 44 % greater envelopment area than that of Foam A, Foam B, Foam C and Foam D, respectively. Under a 75 N load, Hygroflex had a 64, 30, 36 and 42 % greater envelopment area than that of Foam A, Foam B, Foam C and Foam D, respectively.



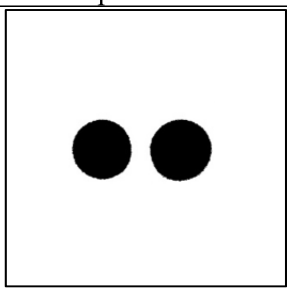
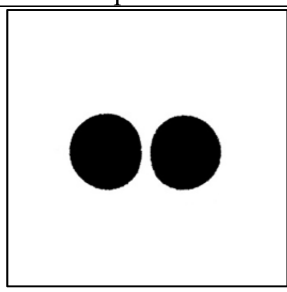
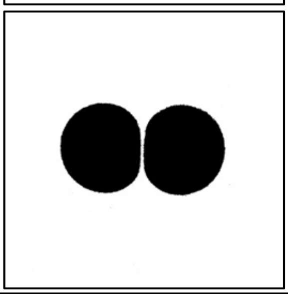
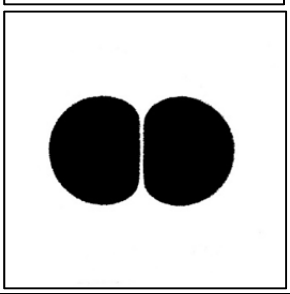
(a)

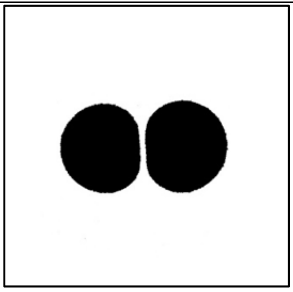
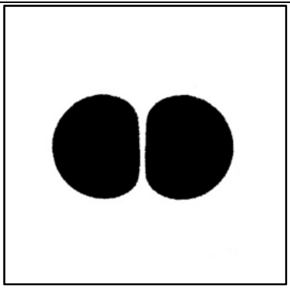
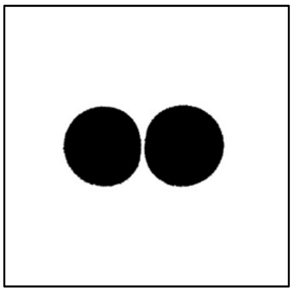
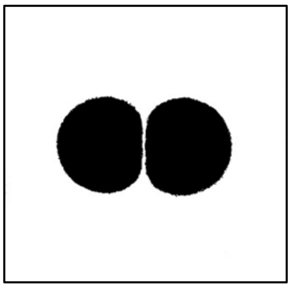
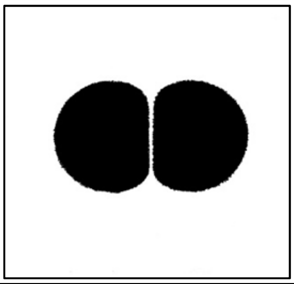
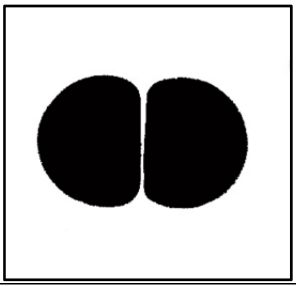


(b)

Figure 2-9: Normalised envelopment area for all foams under (a) 50 N and (b) 75 N loads (all samples were normalised against Hygroflex).

Table 3: Envelopment area for all foams under 50 N and 75 N loads.

Material	Post 50 N envelopment area	Post 75 N envelopment area
A		
B		

C		
D		
Hygroflex		

2.2.5 Implications for Medical Applications

The concept of reducing the development of pressure sores using envelopment is similar to that previously mentioned for immersion. Envelopment refers to the ability of the support surface to conform to the irregularities and contours of the human body, thus providing a greater contact area between the body and surface. Researchers have found variations with contact areas of different support surfaces. Matsuo et al. [6] compared the average contact area for air-filled and urethane foams with varying internal pressures and stiffnesses. They found that greater foam stiffnesses and internal pressures of air-filled mattresses resulted in lower contact areas, and thus higher interface pressures.

The research presented here shows that under two different loads (50 and 75 N), Hygroflex had the greatest contact area. This would result in lower interface pressure as Hygroflex was able to distribute the force over a larger contact area.

2.3 Bulbous Indenter Test

2.3.1 Rationale

The aim of this test was to compare the maximum interface pressure (IP) and pressure distribution of Hygroflex and various other foams after being compressed by representative human buttocks. In the case of formation of pressure sores, this test examines the effect of various foams on the 'magnitude' of pressure or 'peak' pressure generated.

2.3.2 Materials

The bulbous shaped indenter described in Section 2.2 was used again in this test. A Tekscan pressure mapping system was also employed to measure the maximum interface pressure under a fixed displacement and force in two cases.

2.3.3 Methodology

The bulbous shaped indenter was used to compress 400 x 400 x 100 mm foam samples controlled by an Instron 5959 machine with a 10 kN load cell as depicted in Figure 2-10. The indenter compressed the foam under a fixed displacement or force, and was held in compressed condition for two minutes at peak displacement/force. A pressure mat was placed on the surface of the foam to measure the peak and distribution of pressure.

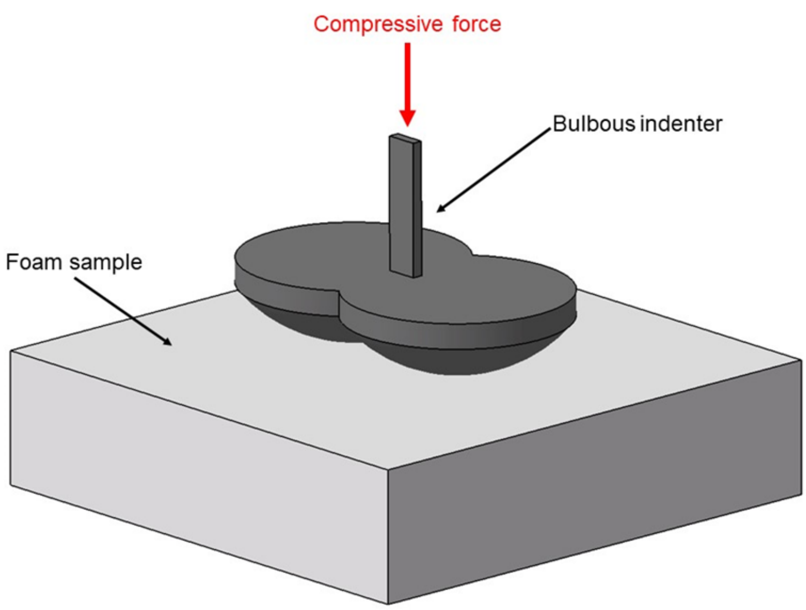
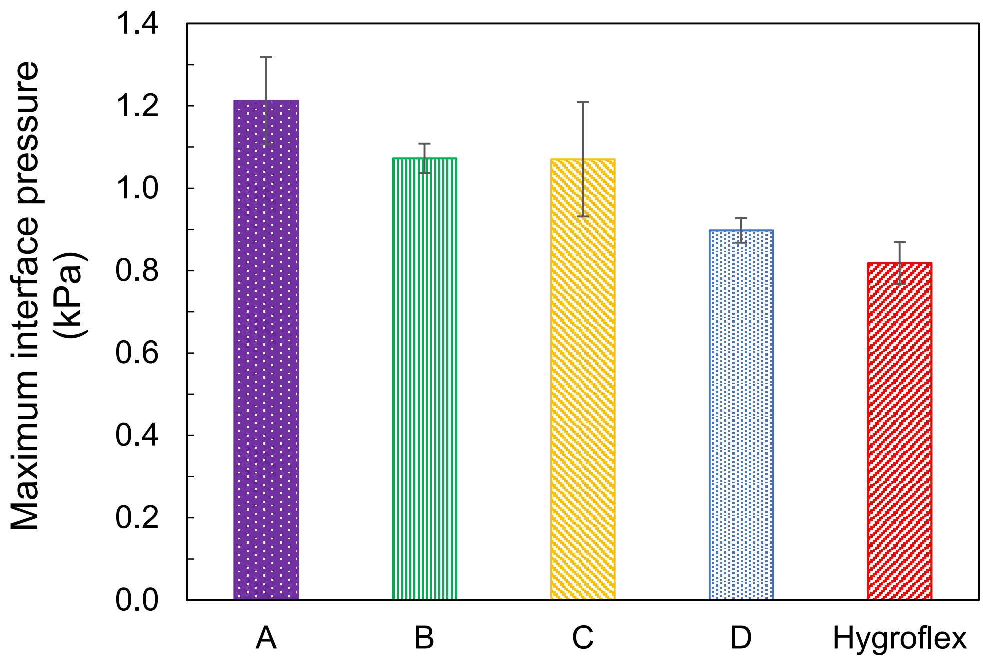


Figure 2-10: Schematic of bulbous indenter test method.

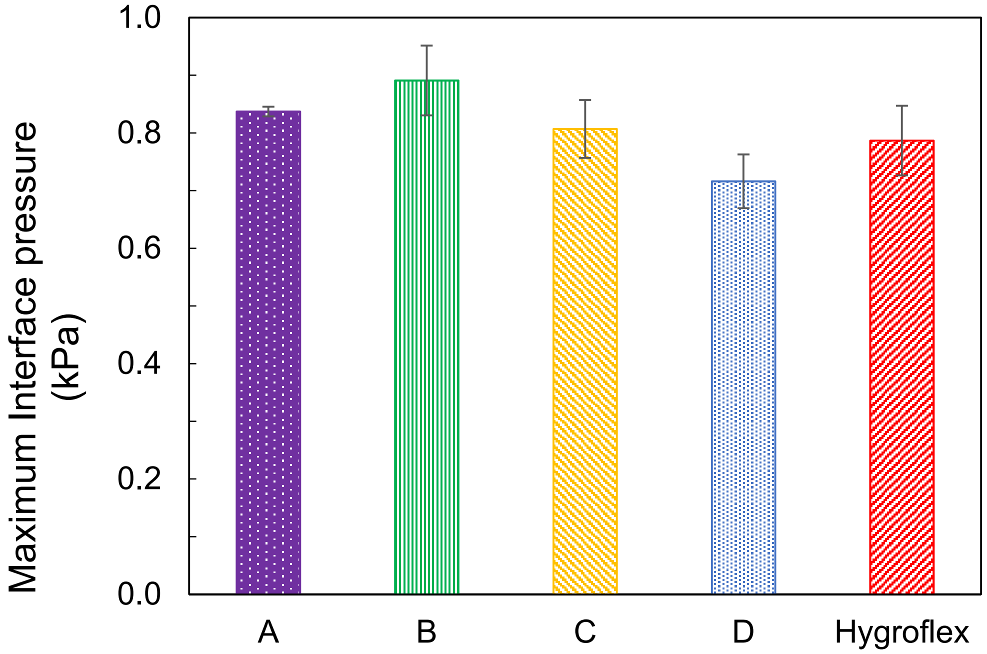
2.3.4 Results

2.3.4.1 Force control

During force control, the bulbous indenter was compressed into the foam until the load transducer on the cross-head read 75 N. The indenter was then held for two minutes before pressure readings were measured. Figure 2-11 depicts the maximum interface pressure over (a) the entirety of the test, and (b) after the two-minute hold. Over the entirety of the test, Foam A had the highest interface pressure (~1.2 kPa). Comparatively, Hygroflex had the lowest interface pressure (~0.82 kPa) after compression under the same force. After the two-minute hold at 75 N compression, Foam A, Foam B and Foam C had similar interface pressures (~0.86 kPa). Comparatively, Hygroflex had an average interface pressure of ~0.79 kPa, which was ~7 % higher than Foam-D.



(a)

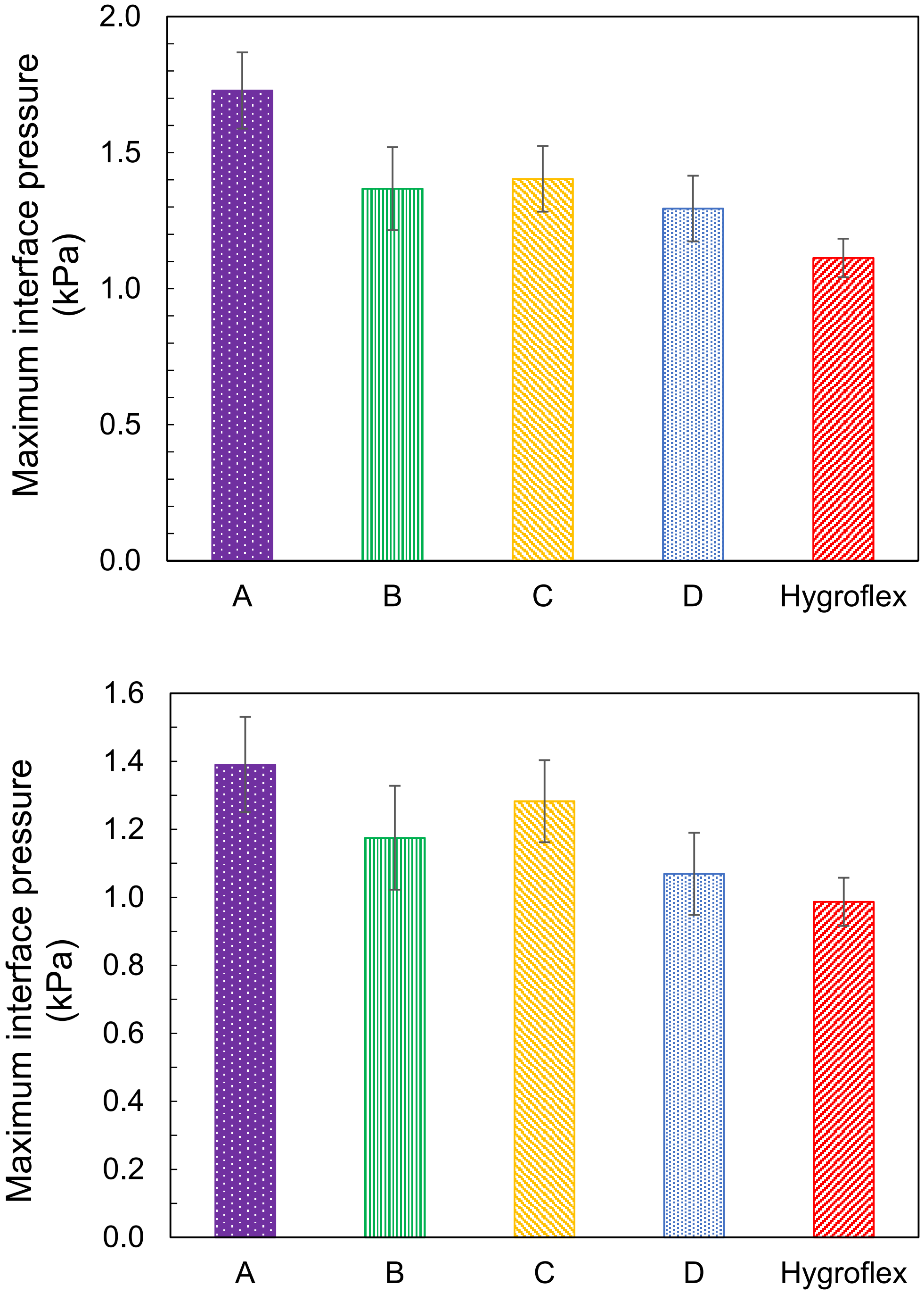


(b)

Figure 2-11: Maximum interface pressure (IP) (a) over entirety of test and (b) after two-minute hold for 75 N force control.

2.3.4.2 Displacement Control

In displacement control, the bulbous indenter was compressed into the foam by 40 mm of the total 100 mm thickness. The indenter was then held for two minutes before the pressure was measured. Figure 2-12 depicts the maximum interface pressure (a) over the entirety of the test, and (b) after the two-minute hold. Over the entirety of the test, Foam A had the highest interface pressure (~1.7 kPa). Comparatively, Hygroflex had the lowest interface pressure (~1.1 kPa) when subjected to the same compression. A similar relationship is observed when comparing the maximum interface pressure after the two-minute hold. Foam A had the highest interface pressure (~1.4 kPa), and Hygroflex had the lowest interface pressure (~0.99 kPa) which was ~8 % lower than Foam D (~1.07 kPa).



(a)

(b)

Figure 2-12: Maximum interface pressure (IP) (a) over entirety of test and (b) after two-minute hold for 40 % strain displacement control.

2.3.5 Implications for Medical Applications

Different support surfaces (e.g. beds, mattresses, mattress overlays and cushions) are designed to relieve pressure around vulnerable parts of the body by distributing the surface pressure evenly. The pressure value for capillary closure in human patients is 32 mm Hg (~4.2 kPa) [9]. Interface pressures between skins and contact (supporting) surfaces higher than this value, if applied for a sufficient period of time, may lead to tissue breakdown [10]. Early studies found that the most crucial interaction in pressure sore formation was the relationship between pressure intensity and duration [11]. In order to assess the effectiveness of the foams in this study, pressure intensity will be evaluated while the duration of pressure remains constant.

A systematic review of support surfaces for the prevention of pressure sores [12] found that the use of alternative foams (compared to a standard hospital mattress) can significantly reduce the incidence of pressure ulcers in at-risk patients. The present research found that under a fixed strain (40 %) and fixed force (75 N), Hygroflex had the lowest maximum interface pressure compared to all the other foams tested. However, once the indenter was held compressed in the foam for two minutes, Foams A-D were also able to effectively distribute the pressure, reducing the difference in maximum interface pressure between Hygroflex and Foams A-D.

2.4 Shear Test

2.4.1 Rationale

The aim of this test was to quantify the shear modulus of Hygroflex and various other foams. The ability to deform vertically as well as horizontally reduces the surface shear force, also known as the 'hammocking' effect.

2.4.2 Materials

A mechanical shear jig was manufactured out of 4 mm thick aluminium. Mechanical grips were designed to fit a 25 x 25 x 25 mm cube of foam.

2.4.3 Methodology

The methodology for the shear test is schematically depicted in Figure 2-13. Samples were placed in between two opposing grips and loaded at 25 mm/min under tension. The geometry of the grips created a shear force on the foam. The force and displacement were exported from the Instron test 5959 machine, allowing the calculation of stress and strain.

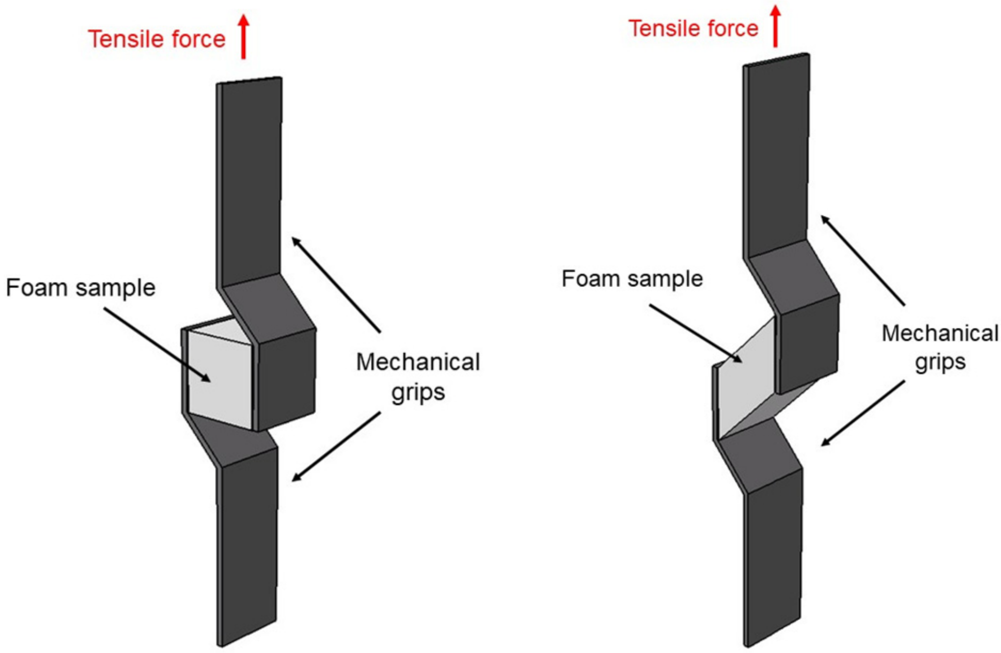


Figure 2-13: Schematic of the shear test with starting position (left) and final position (right).

2.4.4 Results

The shear properties of each of the foams were categorised into initial elastic modulus (before 20 % strain) and post densification modulus (after 20 % strain). The results are shown in Figure 2-15. The results show that the initial slope of Hygroflex was 117 % lower than the closest comparative foam (Foam B). Both Foam A and Foam C had the highest initial shear moduli, which were 196 % and 214 % higher than that of Hygroflex, respectively. In other words, over the first 20 % straining of the foam, it would take approximately three times more force to move laterally for Foam A and Foam C than that required for Hygroflex. However, at higher strain levels, Hygroflex had a similar shear modulus compared to the other foams, except Foam A, which has a ~60 % higher modulus.

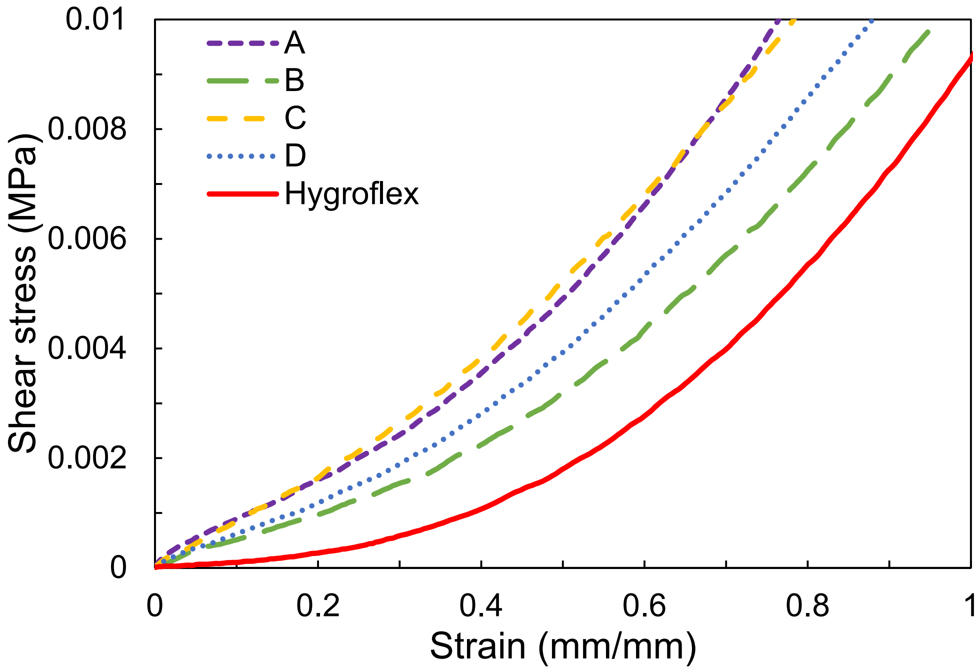
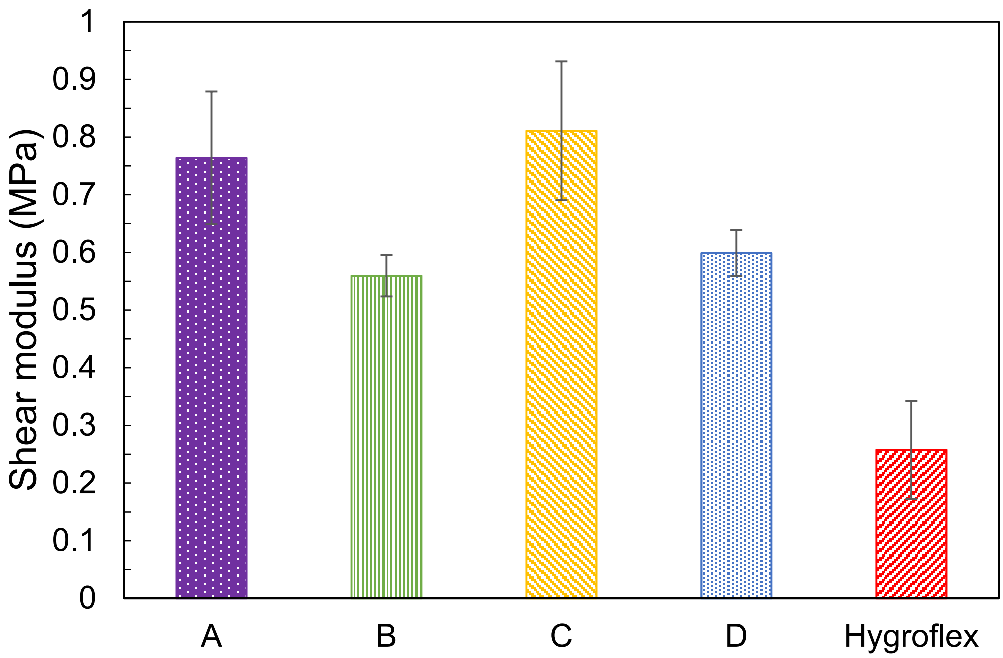
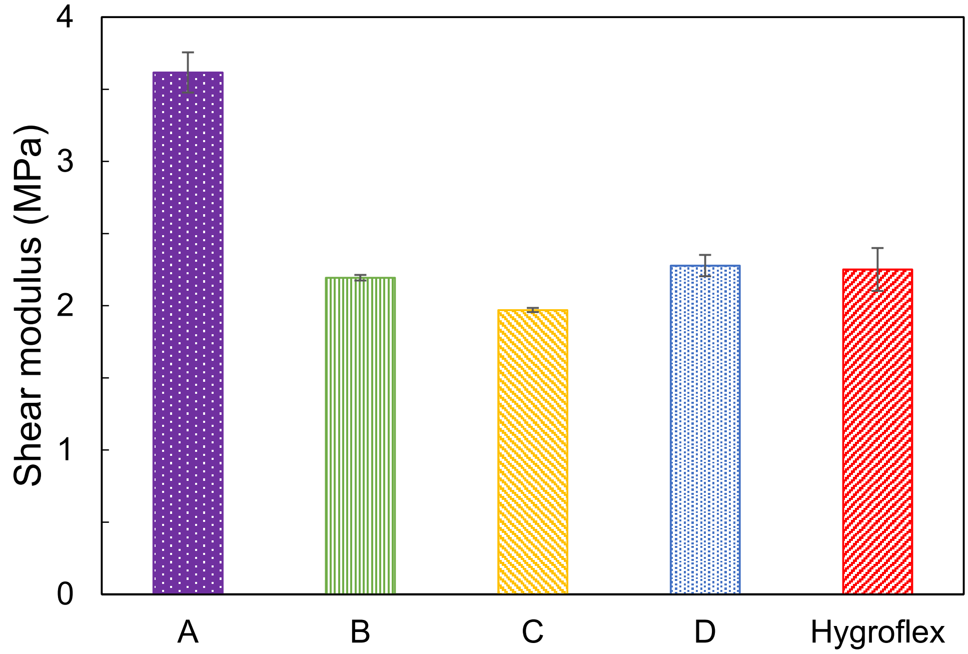


Figure 2-14: Representative shear stress-strain data for all foams.



(a)



(b)

Figure 2-15: Comparison of shear moduli of all foams for (a) initial slope (0.1-0.3 % strain) and (b) post densification (1.0-1.5 % strain).

2.4.5 Implications for Medical Applications

When patients are moved from their bed to a wheelchair or a chair, excess friction causes skin irritation which can lead to ulcers. Likewise, large friction and shear forces are generated when a patient is pulled up in a bed while the skin of the buttock area remains in contact with the bed surface [13]. Researchers have also found that the elbow and heel, due to their small contact area [14], are subject to high interface pressures and shear forces [15]. The reduction in the prevalence of pressure ulcers in the heels and elbows is largely due to the improvement of therapeutic support surfaces [14]. Support surfaces prevent pressure ulcer development by reducing skin-surface contact interface pressure. In general, many support surfaces incorporate a low-friction, low-shear cover that reduces the formation of pressure ulcers from shear forces [16]. This work investigated the ability of support surface foams to move laterally under a shear force.

The study has found that the shear force required for Hygroflex to move in a lateral/sliding motion was at least half of that compared to all other foams tested (over the first 20 % strain of the foam). This would allow the foam to move/slide with the patient's body (as opposed to causing relative motion and hence frictional stress on the skin) with much less resistance.

2.5 Roller-Arm Test

2.5.1 Rationale

The aim of this test was to quantify the force required for a patient already immersed in the foam to roll over.

2.5.2 Materials

The materials used for this test were as follows:

- Movable (free to rotate) tool-steel roller
- Mechanical grip
- Steel wire
- 250 N load cell
- DC motor

2.5.3 Methodology

The methodology for the roller-arm test is schematically represented in Figure 2-16. The movable roller was used to compress a 300 × 80 × 100 mm sample controlled by an Instron 5959 with a 10 kN load cell.

The roller compressed the foam by a fixed 40 % of the initial foam thickness. The indenter was held compressed for two minutes before the test was started. A mechanical grip held the foam from the side and was connected to the DC motor by a steel wire. The DC motor pulled the foam, resulting in a rolling motion of the roller. The force to create this rolling movement was measured using a load cell, which was located between the DC motor and the mechanical grip.

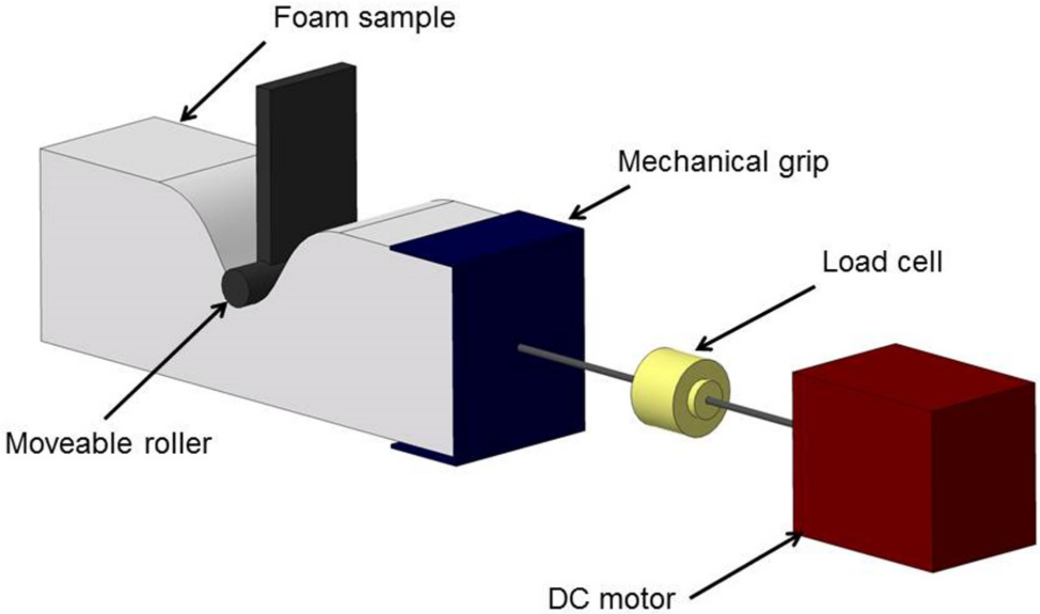


Figure 2-16: Schematic of roller-arm test method.

2.5.4 Results

Figure 2-17 displays representative force-displacement curves for all the foam materials extracted from the load cell. The load initially increased linearly as the roller began to move. The force then increased non-linearly until it reached a peak plateau force. This plateau force was the force required for the roller to complete one full rotation. However, with Hygroflex, the force remained constant after the initial linear force increase. After the initial movement of the roller in the Hygroflex foam, there was no residual force acting on the roller as it continued to roll. With the other foam samples (most notably Foam A), the roller force continued to increase as the roller moved, until it reached a peak plateau force after 50-90 mm displacement. This means that as a patient attempts to complete a full rotation/roll, the movement becomes more difficult in the middle of the roll as there is residual force from the foam acting on the body.

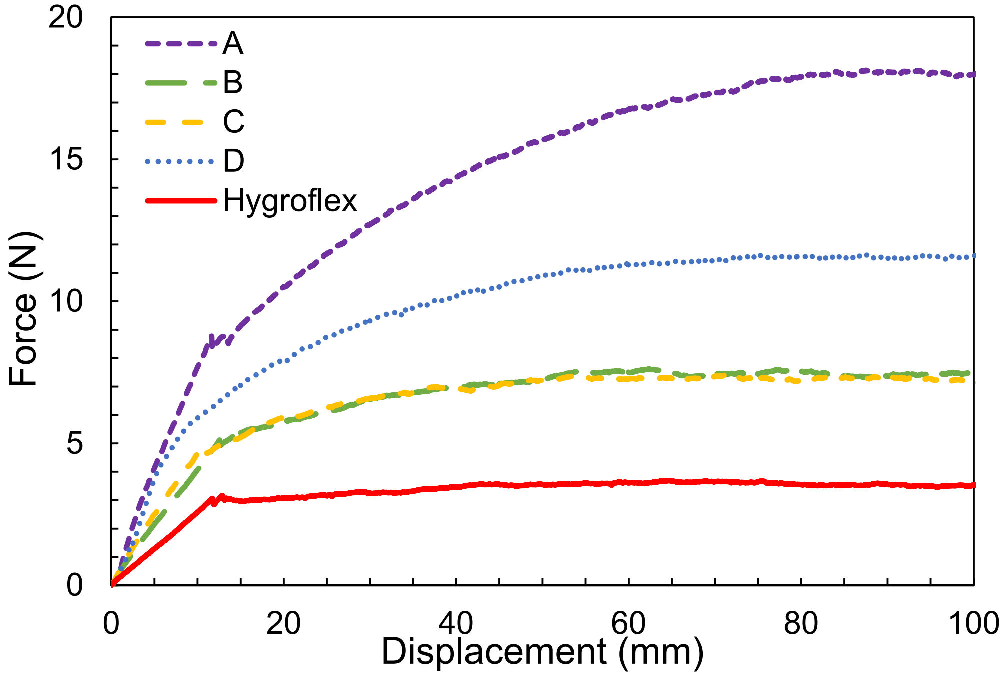
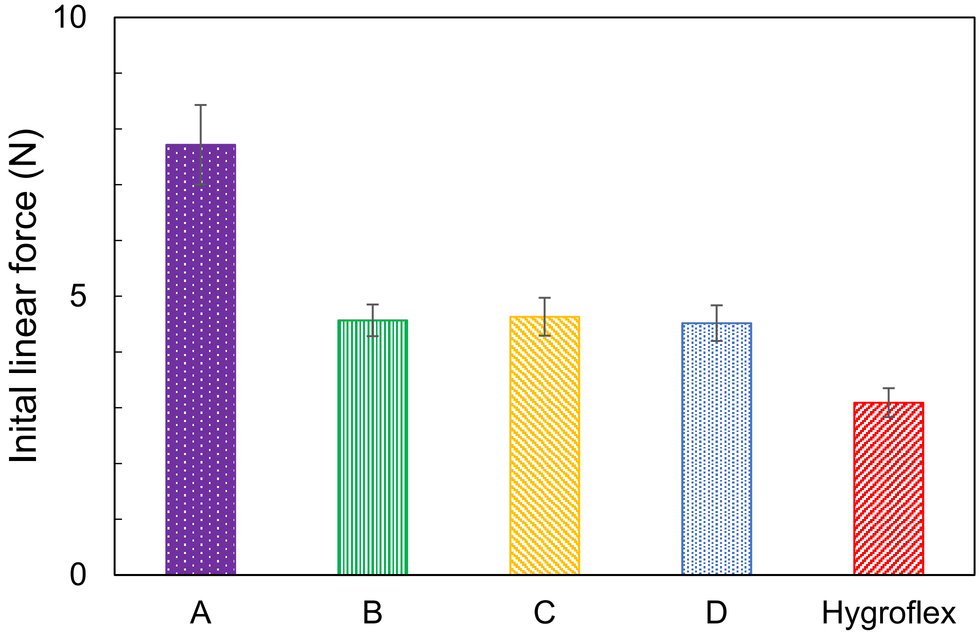
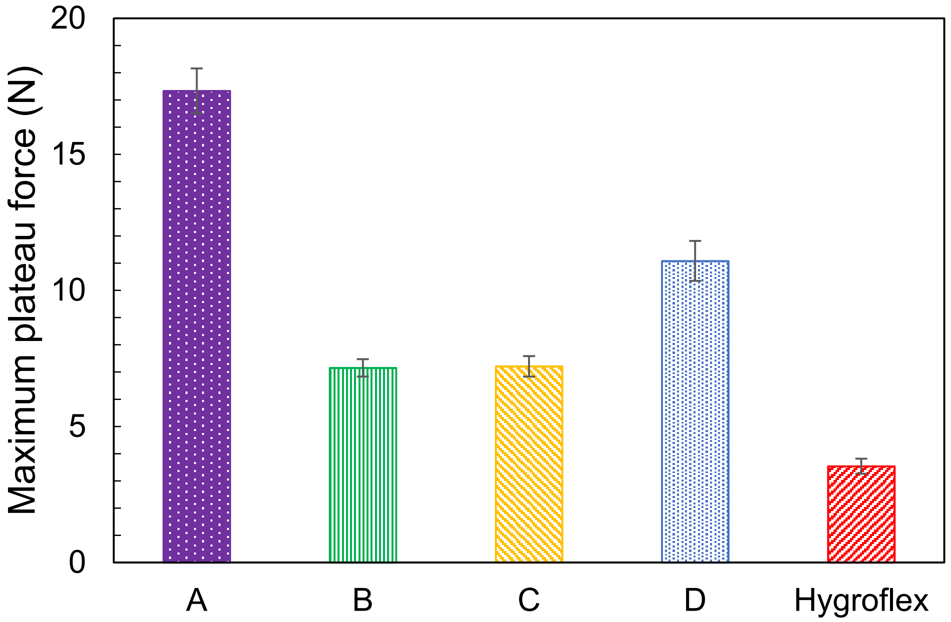


Figure 2-17: Roller-arm test force-displacement curves for all foams.

The force was measured at the peak of the initial linear and plateau region. The results for initial linear force and maximum plateau force for the foams are shown in Figure 2-18. For the initial linear force, Hygroflex had 150, 48, 50 and 46 % lower initial movement force than that of Foam A, Foam B, Foam C and Foam D, respectively. Similarly, for the maximum plateau force, Hygroflex had 390, 102, 104 and 213 % lower maximum rolling force than that of Foam A, Foam B, Foam C and Foam D, respectively.



(a)



(b)

Figure 2-18: Roller-arm test force measurements; (a) linear force due to initiation of movement of the roller and (b) maximum plateau force after the roller completes one full rotation.

2.5.5 Implications for Medical Applications

As previously mentioned, excessive frictional and shear forces are associated with patient movement in bed (e.g. use of trapeze, rolling, placement of bedpan), as well as movement between the bed and another surface or wheelchair/chair [13]. It is widely recognised that shear and friction are large contributors in the development of pressure ulcers [15]. The test procedure described here is novel and is designed to evaluate the foam performance during a rolling or turning motion of a patient lying on a mattress. Normally, shear and frictional forces are mitigated through dressings and top-sheets, however, the support surfaces themselves can also have a significant impact on pressure ulcer formation [15].

In this test, it was found that Hygroflex required a very low force to complete a full rotation/turn (less than half compared to the other foams tested). Therefore, Hygroflex had the lowest resistance to a rolling motion, which would reduce the shear and frictional force on the skin and body.

2.6 Cyclic Test

2.6.1 Rationale

The aim of this test was to quantify the energy loss/dissipation of Hygroflex and other various medical mattresses foam samples.

2.6.2 Materials

The sharp shaped indenter was used to conduct cyclic loading of all the foams.

2.6.3 Test methodology

The sharp shaped indenter was used to compress a 200 x 200 x 100 mm sample controlled by an Instron 5959 machine with a 10 kN load cell. The foam samples were loaded to a fixed 40 % strain, then unloaded until the foam returned to its initial configuration. The samples were loaded and unloaded at a fixed rate of 40 mm/min. The hysteresis loss was calculated as the area between the loading and unloading curves.

2.6.4 Results

Representative force-displacement plots for the foams under cyclic loading are shown in Figure 2-19. The area enclosed by the hysteresis loop (loading and unloading curves) corresponds to the dissipated energy under each cycle. The energy dissipated and hysteresis loss (%) due to the hysteresis loop for all foams is shown in Figure 2-20. The energy dissipation and hysteresis loss for Hygroflex was lower compared to that of the other foams. Hygroflex had an average of ~24 J energy loss which was over three times lower than the next closest sample, Foam C. Similarly, Hygroflex had a hysteresis loss value of ~12 % which was approximately three times lower than the next foam material. Thus, Hygroflex was at least three times more effective than all other tested foams at maintaining its original support characteristics after flexing/compressing.

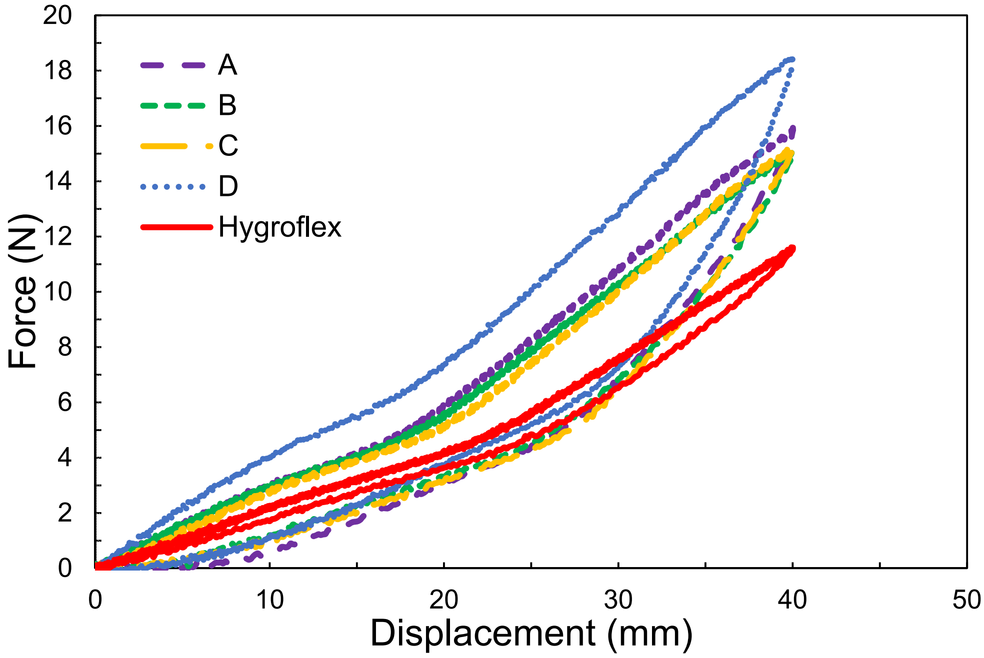
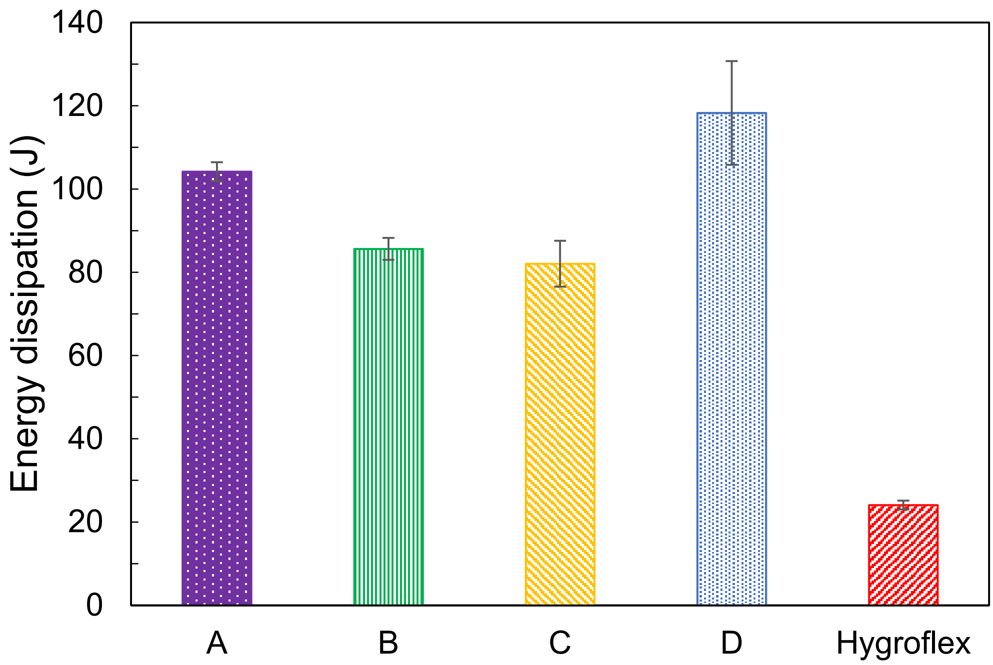
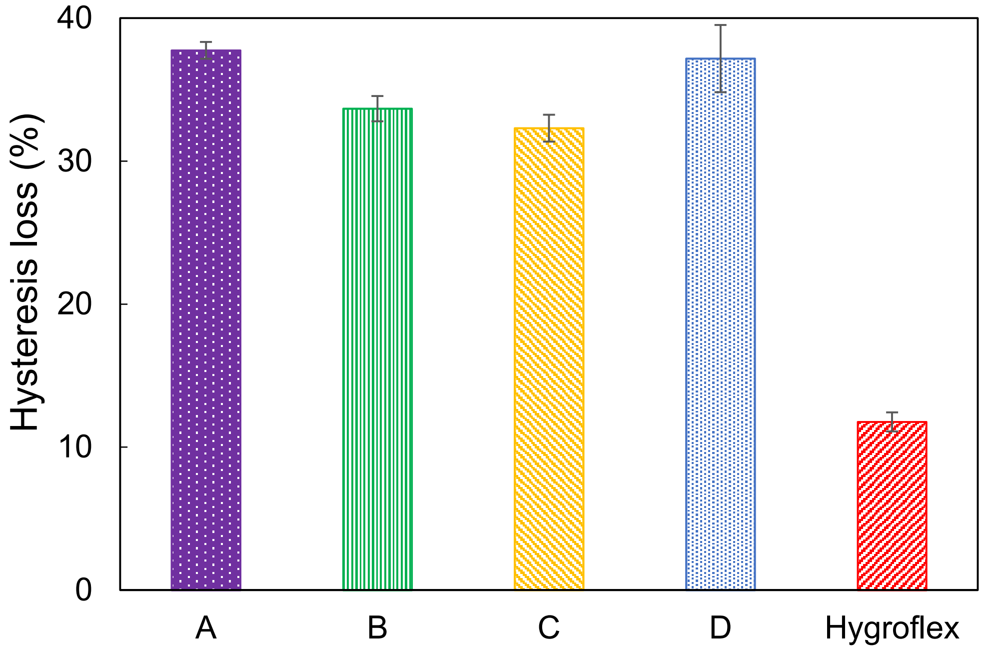


Figure 2-19: Representative force-displacement curves for all foams under cyclic loading.



(a)



(b)

Figure 2-20: (a) Energy dissipated and (b) hysteresis loss calculated from force-displacement curves for all foams.

2.6.5 Implications for Medical Applications

Hysteresis is a measure of a mattress' ability to compress and decompress when a load is applied to it. Low hysteresis means that the energy applied to the material during the loading phase is nearly entirely exerted back during the unloading (i.e. the foam is not absorbing the energy). A high hysteresis is the result of a large amount of energy being dissipated by the material during the unloading phase, resulting in a delayed response of the material (common in memory foams). This makes it more difficult for patients to move or roll in a high hysteresis material compared to a low hysteresis material. Research by Shen et al. [17] found that patients sleeping on mattresses with high hysteresis had a lower percentage of deep sleep and sleep efficiency (ratio of total sleep time to time spent in bed) compared to other mattresses with lower hysteresis.

The work presented here demonstrates that Hygroflex had a significantly lower hysteresis compared to Foams A-D. This test demonstrated that a lower hysteresis loss would result in less resistance when a patient attempts to move/roll. Low hysteresis foams have also been linked to higher comfort levels for patients [17], resulting in better sleep efficiency.

2.7 Thermal Test

2.7.1 Rationale

The aim of this test was to quantify specific heat capacity, thermal conductivity and diffusivity coefficient of all the foam materials.

2.7.2 Definitions

Specific heat capacity (c) relates to the amount of heat energy required to raise the temperature of the unit mass of a given substance or material by a given amount (usually 1 degree). Low heat capacity means it does not require much heat energy to heat and cool the material.

Thermal conductivity (k) relates to the heat transfer rate within a material. Heat transfer occurs at a lower rate in materials with low thermal conductivity than in materials with high thermal conductivity.

Thermal diffusivity (α) measures the rate of heat transfer of a material from the hot side to the cold side. In a substance with high thermal diffusivity, heat transfers rapidly through it.

2.7.3 Materials

For this test, the following materials were used:

- Calibrated environmental chamber
- 2 x thermocouples
- Insulated box
- Temperature logging software

2.7.4 Test methodology

Small (25 x 25 x 25 mm) cubed samples were inserted into a 50 ^{0}C controlled chamber. Thermocouples were positioned on the surface and in the centre of the foam. Samples remained in the chamber until they reached 50 ^{0}C internal temperatures, after which they were placed in a controlled ambient temperature chamber. The samples were maintained in the ambient temperature chamber until the internal temperature of the foam was 20 ^{0}C.

The calculations for specific heat capacity were based on the lumped capacitance model (Equation 1), whereby it is assumed that the temperature is uniform throughout the material at any given time.

$$\frac{T_\infty - T}{T_\infty - T_i} = e^{-\left(\frac{hA}{mc}\right)t} \qquad \text{Equation 1}$$

where T_∞ is the temperature of the chamber, T is the current temperature of the material, T_i is the initial temperature of the material, h is the convective heat transfer coefficient (assumed to be constant across all materials), A is the surface area, m is the mass, t is the time and c is the specific heat capacity.

The calculations for thermal conductivity were based on Fourier law (Equation 2), whereby the temperature through-the-thickness of the foam is variable.

$$\mathbf{q_x} = -\mathbf{kA}\left(\frac{\mathbf{T_c}-\mathbf{T_0}}{\mathbf{x_c}-\mathbf{x_0}}\right) \qquad \text{Equation 2}$$

where; q_x is the heat flux density (in the x-direction assumed to be constant across all materials), A is the surface area, T_{ic} is the temperature on the outside of the foam, T_0 is the temperature in the centre of the foam, x_c is the location of the centre and x_0 is the distance from the centre to the foam surface.

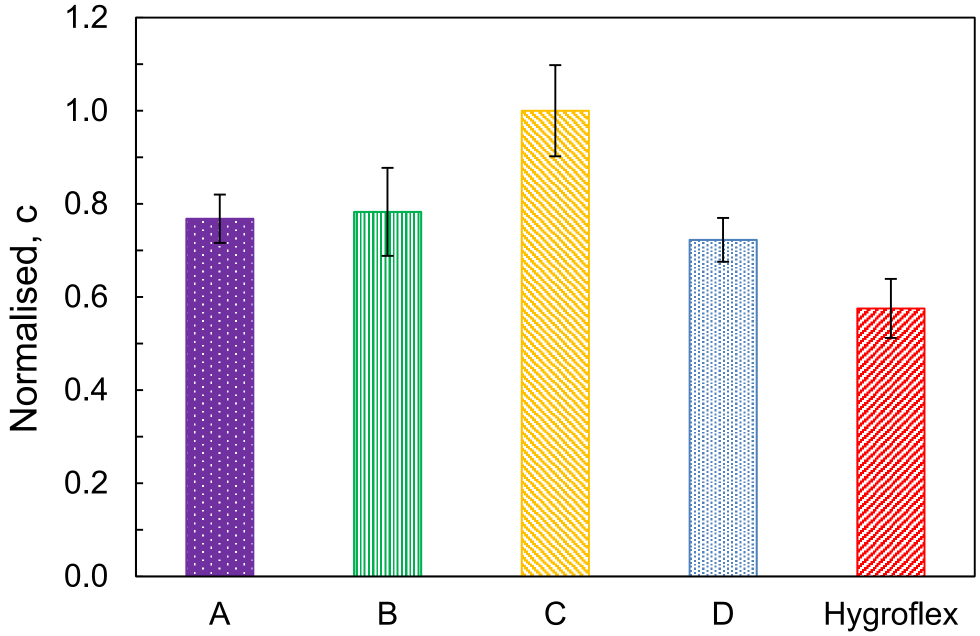
The calculations for thermal diffusivity were based on the following equation (Equation 3):

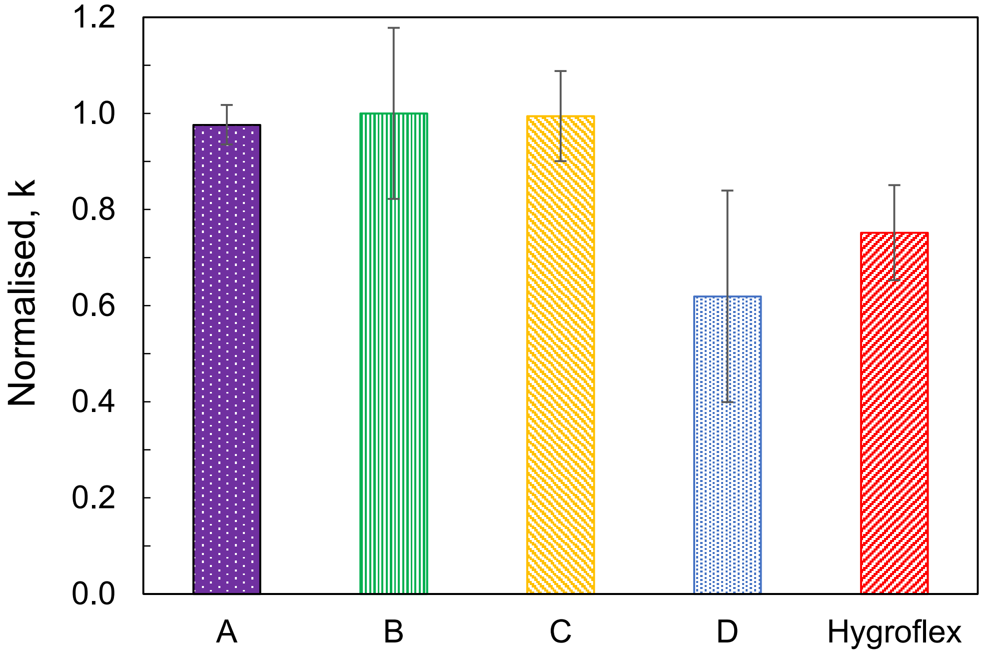
$$\alpha = \frac{k}{\rho c} \qquad \text{Equation 3}$$

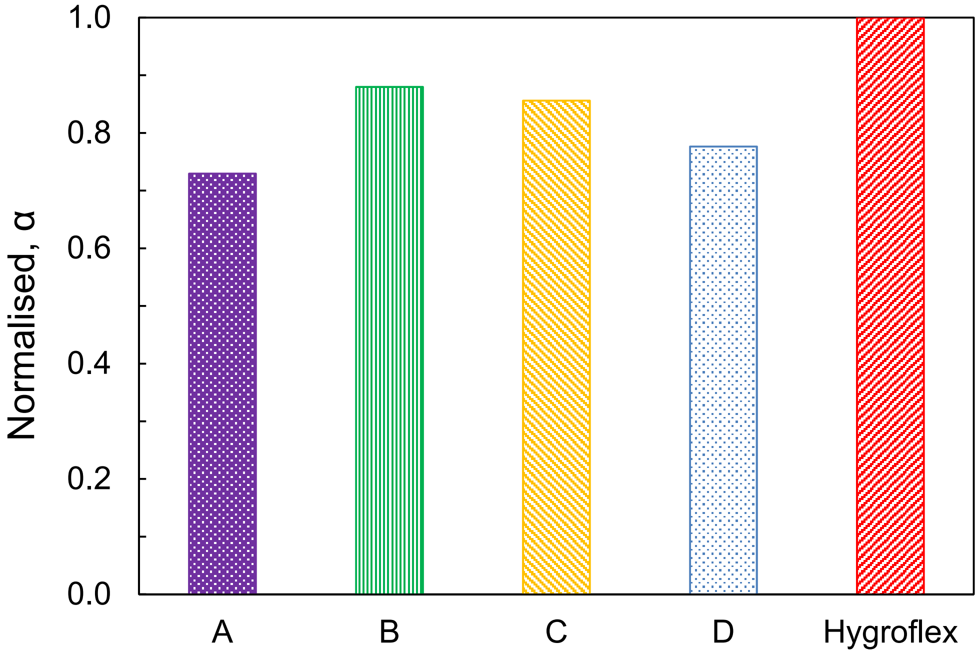
where α is the thermal diffusivity coefficient, k is the thermal conductivity, c is the specific heat capacity, and ρ is the material density. Note it is a non-dimensional parameter and can thus be used to compare thermal properties of various foams.

2.7.5 Results

The thermal test results are presented below.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Normalised, c
A
B
C
D
Hygroflex
(a)


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Normalised, k
A
B
C
D
Hygroflex
(b)



(c)

Figure 2-21: Normalised (a) specific heat capacity (c), (b) thermal conductivity (k) and (c) thermal diffusivity (α) for all foam materials.

2.7.6 Implications for Medical Applications

Previous research has found that temperature has a significant role in the development of pressure ulcers. Lachenbrunch et al. [18] found that a 1 ^{o}C increase or decrease in temperature has as much effect on the reactive hyperemia as an 8-15 mm Hg increase or decrease in interface pressure.

Studies have found that an increase in the local skin temperature caused by pressure application [19] and insulating effect of cushions/mattresses [20] greatly enhances the formation of pressure sores. Kokate et al. [21] developed a model based on swine to find the relationship between applied temperature, applied pressure, and the time of application in the formation of cutaneous and deep tissue injuries. They found that the local application of 100 mm Hg of pressure for 5 hours at 45 ^{o}C caused full thickness cutaneous and deep tissue injury, whereas the same pressure and time duration applied at 25 ^{o}C resulted in no damage.

The work presented here demonstrates that Hygroflex had the highest thermal diffusivity coefficient compared to all the other foams tested. Hygroflex had approximately 27, 12, 14 and 22 % higher thermal diffusivity compared to that of Foams A, B, C and D, respectively. If heat were to be applied to one side (in the case of a patient lying on the mattress), the heat energy generated from the body will transfer through a Hygroflex mattress faster compared to the other tested foams.

3 Summary

The present work has studied several properties of interests of a variety of memory foams, including the newly developed Hygroflex foam, in order to assess their relative performance and effectiveness in relation to usage in medical mattresses. The key characteristic evaluated are the peak pressure generated, pressure re-distribution over the immersed surface of the foam in contact with simulant body parts, and the immersion and wrap effects under body part induced deformation. The mechanical tests conducted were; a sharp indentation test, an envelopment test, a bulbous indentation test, shear tests, a roller arm test, and a cyclic test. A thermal test was also conducted to assess the heat dissipation ability of the various foams. The test results demonstrate that the newly developed Hygroflex foam has superior mechanical properties required in medical mattresses, compared to other variants of memory foams studied.

In future, there are opportunities to develop new test processes and improve the ones used in this work. One key area that could be investigated is the analysis and testing of layered foams (even including mattress covers), simulating their usage in mattresses.

References

1. Kouchi, M., *Foot dimensions and foot shape: Differences due to growth, generation and ethnic origin.* Anthropological Science, 1998. **106**(SUPPL.): p. 161-188.

2. Krauss, I., et al., *Sex-related differences in foot shape.* Ergonomics, 2008. **51**(11): p. 1693-1709.

3. Krishan, K., *Estimation of stature from footprint and foot outline dimensions in Gujjars of North India.* Forensic Science International, 2008. **175**(2): p. 93-101.

4. Voracek, M., et al., *Sex Differences in Relative Foot Length and Perceived Attractiveness of Female Feet: Relationships among Anthropometry, Physique, and Preference Ratings.* Perceptual and Motor Skills, 2007. **104**(3_suppl): p. 1123-1138.

5. Dealey, C., et al., *Challenges in pressure ulcer prevention.* International wound journal, 2015. **12**(3): p. 309-312.

6. Matsuo, J., et al., *Development and validity of a new model for assessing pressure redistribution properties of support surfaces.* Journal of Tissue Viability, 2011. **20**(2): p. 55-66.

7. Pipkin, L. and S. Sprigle, *Effect of model design, cushion construction, and interface pressure mats on interface pressure and immersion.* 2008.

8. Standardization, I.O.f., *Wheelchair seating -- Part 2: Determination of physical and mechanical characteristics of seat cushions intended to manage tissue integrity.* 2018.

9. Landis, E.M., *Micro-injection studies of capillary blood pressure in human skin.* Heart, 1930. **15**: p. 209-228.

10. Daniel, R.K., D.L. Priest, and D.C. Wheatley, *Etiologic factors in pressure sores: an experimental model.* Archives of physical medicine and rehabilitation, 1981. **62**(10): p. 492-498.

11. Husain, T., *An experimental study of some pressure effects on tissues, with reference to the bed-sore problem.* The Journal of Pathology and Bacteriology, 1953. **66**(2): p. 347-358.

12. McInnes, E., et al., *Support surfaces for pressure ulcer prevention.* Cochrane Database of Systematic Reviews, 2015(9).

13. Hanson, D., et al., *Friction and shear considerations in pressure ulcer development.* Advances in skin & wound care, 2010. **23**(1): p. 21-24.

14. Nakagami, G., et al., *Comparison of Two Pressure Ulcer Preventive Dressings for Reducing Shear Force on the Heel.* Journal of Wound Ostomy & Continence Nursing, 2006. **33**(3): p. 267-272.

15. Brienza, D.M. and M.J. Geyer, *Understanding support surface technologies.* Advances in skin & wound care, 2000. **13**(5): p. 237.

16. Bree-Aslan, A. and S. Hampton, *Parafricta and the prevention of shearing forces: heel ulcers.* Nursing And Residential Care, 2008. **10**(2): p. 78-80.

17. Shen, L., et al., *Research on the relationship between the structural properties of bedding layer in spring mattress and sleep quality.* Work, 2012. **41**(Supplement 1): p. 1268-1273.

18. Lachenbruch, C., et al., *The relative contributions of interface pressure, shear stress, and temperature on tissue ischemia: a cross-sectional pilot study.* Ostomy/wound management, 2013. **59**(3): p. 25-34.

19. Mahanty, S.D. and R.B. Roemer, *Thermal response of skin to application of localized pressure.* Archives of physical medicine and rehabilitation, 1979. **60**(12): p. 584-590.

20. Fisher, S.V., et al., *Wheelchair cushion effect on skin temperature.* Archives of physical medicine and rehabilitation, 1978. **59**(2): p. 68-72.

21. Kokate, J.Y., et al., *Temperature-modulated pressure ulcers: a porcine model.* Archives of physical medicine and rehabilitation, 1995. **76**(7): p. 666-673.