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Mechanical properties of polyurethane foam for potential application in the prevention and treatment of pressure ulcers

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ABSTRACT

The viscoelastic property is a crucial parameter for evaluating the feasibility of the foam to be used as pressure relief. This work aims to perform experimental measurements to determine the dependence of the viscous behavior of polyurethane foam on density and energy dissipation. Experimental measurements were realized for three types of polyurethane foams with different densities soft, medium and hard. The compression tests at room temperature characterized the mechanical properties of these samples. Furthermore, the structures of the samples were characterized using scanning electron microscopy (SEM). A proportional relationship was observed between the density of polyurethane (PU) foam and the tolerated strength at 90% compression. This material has an excellent remanence (persistence) which showed by the creep experiments at constant stress (2, 5, 10 N) for 6 h. Young Modulus, relaxation time and dissipation coefficient (DE) were also calculated from the stress-strain curve. Moreover, softening behavior, which is responsible for pressure relief, was measured by a cyclic compression test. This paper assesses the capacity of polyurethane to effectively maintain interfacial pressure below the critical threshold of 32 mm of mercury, which represents a significant risk level for the development of pressure sores.

1. Introduction

A pressure ulcer is a localized lesion of the skin or underlying tissues caused by pressure on a bony prominence and the supporting surface, which causes microvasculature blockage and ischemia. As a result of tissue hypoxia, tissue deformation can develop in the region. The prevention strategies are generally based on reducing the impact of pressure, shear force and friction which are the mechanisms that lead to the development of pressure ulcers.

Polymeric foams have a vast range of applications [1–6] and especially polyurethane foams which are more and more used in industry. Due to their high energy absorption, polyurethane is widely used in vibration isolation, noise damping and shock absorption. This property makes polyurethane a good choice in several fields such as aeronautics, automobile, construction, packaging and biomedical industries [7,8].

Polyurethane consists of two main components, which are polyol and isocyanate, polyol represents a soft segment of the polymer, and isocyanate presents the hard segment. The mechanical properties, including the strength, hardness and viscoelastic of polyurethane, depend on the chain's length of the polyol reacting with the isocyanate [1,9,10], whereas polyurethanes with long polyol chains result in more flexible structures [11]. The polyol functionality determines the character and degree of crosslinking or branching of the final polymer [12]. In general, increasing the degree of branching means that the final polymer one will have increased ductility, lower elongation at break and a higher glass transition temperature.

In addition, the mechanical behavior is affected by the temperature and the cellular structure inside the foam [13–17]. In the case of open-cell structures with a low completely closed cell content, soft polyurethane foam is observed and characterized by its flexibility and ease of recovery, even when external forces are applied to the deformations.

On the other hand, the rigid foam has many closed cells that form independently of the wall and let it be more used in insulation performance [18,19].

Therefore, it seems interesting to describe the mechanical properties

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of commercial polyurethane foams, which are intended to be used as pressure relief in preventing and treating pressure ulcers. The microstructural characterization was done for three densities (soft, medium, hard) of the polyurethane foam by the scanning electron microscope (SEM). The compression essay evaluated the viscoelastic behavior, which can directly reveal the strain rate sensitive behavior of the material in its stress-strain curves at 0.1, 1, 10 mm/s of strain rate. In addition, the young modulus and tolerated energy were measured by this test.

The creep test was also carried out to evaluate the stability of the foam at 2 N, 5 N and 10 N of constant stress for 6 h of compression, since after 6 h of use as pressure relief, the patient's position must be changed. The creep test is using either constant or cyclic load, in order to determine the performance of foam. This test shows how well the foam retains its original strength and thickness before and after the compression and decompression test in a specific amount. Foam life and performance will vary depending on the foam's density and the amount of load to which the foam is exposed during usage and loading time. A cyclic loading test provides information on the loss of strength of foam [20].

We are interested in a hysteresis loop that measures the energy absorbed by each foam. This information helps to select the foam density for the target part of the body (heel, sacrum, elbow). This work is part of developing a medical device to prevent pressure ulcers. This research aims to justify the pressure dissipation performance of polyurethane foam.

2. The materials

Experimental measurements were carried out on three different densities (soft - medium-hard) of commercial polyurethane foams, supplied by the company COP-Chimie (Saint-Nazaire-en-Royans, France). These foams were studied under the scanning electron microscope (SEM) to characterize their morphology and porosity. The tested samples are cylinders with 2.5 cm in diameter for 2.5 cm in height.

3. Methods

3.1. Compression test

Compression tests are done by a texture analyzer (TAX-T2; texture technologies). The principle of a compression test is an application of a vertical force on the polyurethane foam up to a given percentage of deformation (strain). Two tests were carried out with two deformations 50% and 90%. The 50% deformation test is done to evaluate the viscoelasticity of the material. The objective of the 90% of deformation is to measure the maximum force tolerated by the material without breaking. Young's Modulus and hysteresis loop of the three densities (soft-medium-hard) of polyurethane foam were determined on the base of this test. Moreover, a creep test was carried out to measure the stability of the foams for 6 h of compression at constant stress (2 N, 5 N, 10 N). The measurements were repeated three times for each sample (on different specimens) and the data presented for each sample corresponding to the average of the recorded values.

3.2. Cyclic compression tests

Compression tests evaluate the stress-strain behavior in the cyclic loading-unloading system with a constant strain rate (1 mm/s). The compressed foams were 2.5 cm in diameter and 2.5 cm in height. This test was carried out with a texture analyzer (TAX-T2; texture technologies). The displacement of the actuator is controlled by a constant true strain rate waveform generated by a computer with a TA program. In this machine, the foams were compressed between hardened steel compression plates.

3.3. Relaxation times

The relaxation test provides valuable information about the viscoelastic properties of a material, including its ability to recover from deformation and its time-dependent behavior. It shows the decrease in stress or load over time. The polyurethane foam is subjected to a constant deformation, typically set at 50%. Once the desired deformation is reached, the load or stress is held constant, and the relaxation process is observed and recorded over 20 min.

4. Results

4.1. Morphology of the primary pores

The morphology of primary pores was investigated using scanning electron microscopy (SEM) (Fig. 1). It can be seen in Table A.1 that the pore's area of the three foams of polyurethane differ from 122.8 $\pm$ 146.4 nm for rigid polyurethane, 440.4 $\pm$ 154.1 nm for medium polyurethane and 909.1 $\pm$ 124.6 nm for soft polyurethane and it is similar to the percentage of the pores differ from 22.21% for hard, 34.26% for medium and 36.94% for the soft foam of polyurethane. It is clear that the lowest values of the pore's area and the porosity density appear with the rigid polyurethane, but the highest values of the pore's area and highest density of porosity appear with the soft polyurethane, this means that the hardness of the foam is dependent on the pore's area and the density of porosity.

Barrand. et al. approved that the dissipated energy increases as the pore diameter decreases [21], which agrees with our results that the more rigid foam has the smallest pore diameter and the highest dissipation factor because the harder foam has the highest viscous properties, as will be seen in the creep test.

4.2. Compression tests

Supports are recommended in the prevention and treatment of patients at risk and/or already suffering from a pressure ulcer, and their use should constitute part of an overall preventive or curative strategy. The viscoelastic behavior is essential for the desired application because it is responsible for damping the pressure; therefore, this work evaluates the damping and softening effects of the three densities of polyurethane foam by measuring its viscous behaviors.

Fig. 2 shows the mechanical behavior of polyurethane foam, as obtained from stress-strain curves under 50% of deformation at three different strain rates (0.1, 1, 10 mm/s); it allows to demonstrate the nearly linear elastic regime ending with limiting load; a load plateau follows this stretched to an average strain of approximately 50%, followed by a second stiff branch. The polymer in question has viscoelastic properties, so the hysteresis loop is traced on the unloading curve. The loading plateau is responsible for excellent energy absorption characteristics, while the deformation recovery makes polyurethane foam useful in cushioning.

The values of the compressive modulus for all analyzed polyurethane foams, which were obtained at 0.1, 1, 10 mm/s of strain rates, are given in Table A. 2. The influence of foam density on the mechanical properties was evaluated in this study.

The measurement results showed that the increasing value of the compressive modulus is related to the foam density and strain rate. A similar increase occurred for the tolerated strength at 90% compression from 45.65 $\pm$ 1.16 N for the soft foam to 80.21 $\pm$ 4.29 N for the medium and 132.26 $\pm$ 4.65 N for the rigid foam at 0.1 mm/s.

Therefore, Young's modulus has a direct correlation with the polyurethane density. The harder the foam, the higher Young's modulus value.

Above 60% of compression, the resistance increases significantly, which means the more the foam deforms, the more it resists pressure. The supported energy represents the energy associated with a certain

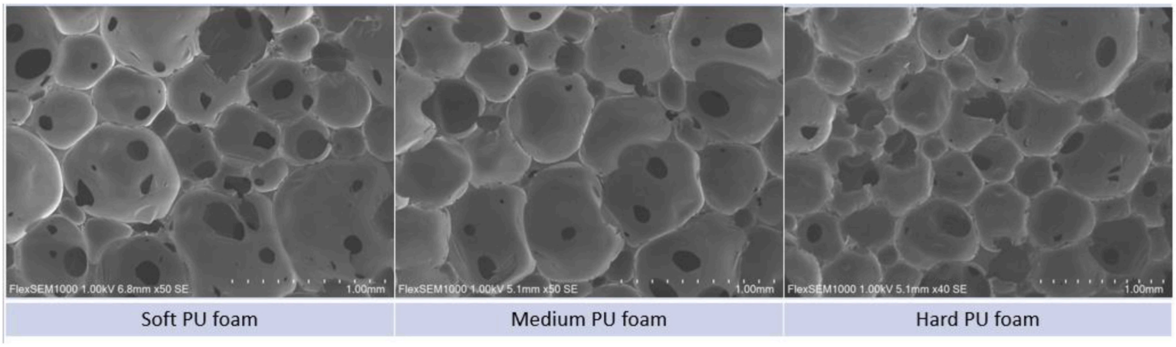

Fig. 1. The SEM images of primary pores (a) Polyurethane Soft, (b) Polyurethane Medium, (c) Polyurethane Hard.

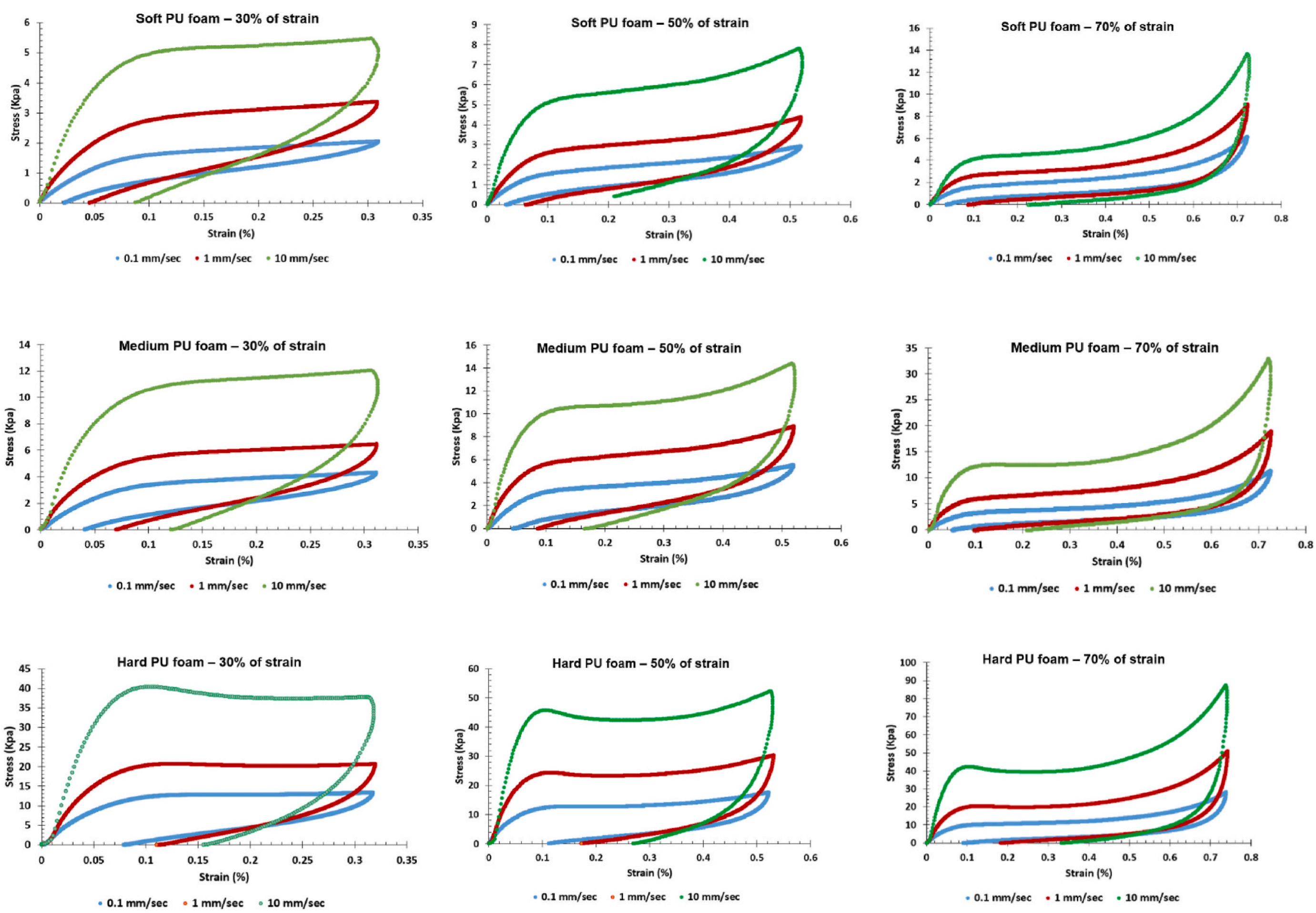

Fig. 2. Stress-strain curve at different rate strains (0.1, 1, 10 mm/s) for the three densities of Polyurethane foam (Soft, medium and hard).

level of material compression. This test demonstrates the absence of a sudden rupture at 90% of compression.

As logically expected, the force at a given deformation value gradually increases as the density of the polyurethane foam increases. This information is essential for the stability of the foam that will be used on the target part of the body.

The influence of the strain rate is also related to the foam's density (Fig. 2), that why the more rigid foam at the higher strain rate required more force to achieve the same deformation.

The dissipation coefficient (DE) is defined as the ability of a material to dissipate energy [22], and the Formula [Eq. (A.1)] is:

$$DE = u/\ (u + w)\ X\ 100\% \tag{A.1}$$

The energy density (U) of the hysteresis curve indicates the dissipative energy under cyclic deformation. The strain energy density (w) indicates the amounts of undissipated energy under cyclic deformation; this means that the air under peak between the two parts (compression and decompression) of each stress-strain curve in Fig. 2 represents the energy dissipated under cyclic deformation. As a result, the harder the foam is, the more energy is dissipated (Fig. 3).

The dissipation coefficient (DE) was measured at 30%, 50% and 70% of deformation with three different strain rates (0.1–1 – 10 mm/s). These deformations were predicted as simulating the use of polyurethane foam as a pressure relief device.

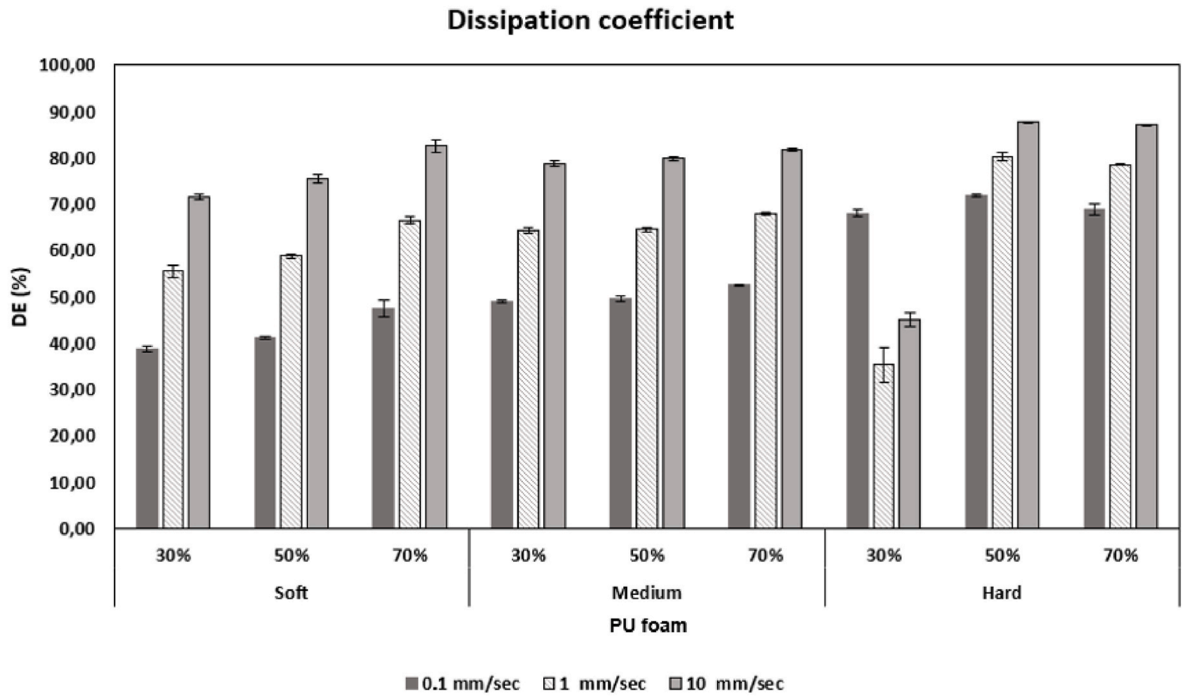

Fig. 3. The dissipation coefficient (DE) for Polyurethane foams (soft, medium and hard) at 30, 50 and 70% of deformation.

4.3. The cyclic loading stress-strain curve/softening behavior

Cyclic softening behavior is observed in these samples by conducting consecutive loading-unloading-reloading on the three different densities of polyurethane foams. A texture analyzer machine carried out the cyclic loading tests controlled by certain total strain at a constant strain rate of 1 mm/s at room temperature. The cycle loading - unloading expressed 10 times.

Fig. 4 shows the compressive stress-strain behavior during the cyclic loading-unloading tests with 15% and 50% strain. Several features are observed. The second cycle of the stress-strain curve deviates from the first cycle. This effect is referred to as softening behavior which is required for the anti-bedsore devices because the softening behavior is responsible for pressure relief. As well as, the softening depends on strain history where the larger strain produces more remarkable softening, so the softening effect at 50% of strain is more significant than 15%.

The foams tend to stabilize after a few cycles, with most of the softening that occurred during the second cycle. The hysteresis loop between the loading and unloading cycle confirms the foam's ability to dissipate energy even during prolonged use.

4.4. Creep test

When a polymeric material is subjected to initial constant stress, it deforms quickly to a strain roughly predicted by its stress-strain modulus and then continues to deform slowly with time. This phenomenon of time-dependent deformation under constant load is denoted as creep [23–25]. At higher loads and longer times, the polymer can be torn, whereas failure may never happen at a low load and time. It is well recognized that the creep behavior of elastomers (thermoplastic or crosslinked) can play an essential role in their applications. The extent of creep depends on several factors, such as the magnitude of the initial stress applied, loading time, temperature, chemical structure, morphology, and topology (i.e., uncross-linked versus crosslinked) of the polymer.

If the material is purely elastic, the creep strain or the deformation will be immediate. Otherwise, in the case of a viscous material, the creep strain will not be immediate and will be associated with the time that's a sign of viscous behavior. When the creep strain is up to 60%, the viscosity behavior will be visible (Fig. 5) and the polyurethane foam can dissipate energy. On the other hand, when the deformation is above 60%, the viscosity will disappear, and the elastic behavior will dominate. Consequently, the polyurethane foam will not be able to dissipate sufficient energy.

When the experiment was performed on the polyurethane foams at different constant stress' (2, 5, 10 N), the creep rate or the slope of the strain-time curve increases with increasing the deformation of the foam (Fig. 6), this deformation increases with decreasing viscosity behavior.

The constant compression set is used to measure the ability of a polymer to preserve its elastic properties after being subjected to compression at room temperature for 6 h. Since the thickness after compression of all the samples used in this test was the same thickness as the original sample, we have a 0% compression set, and the polymer has an excellent remanence after 6 h of compression (Fig. 5).

4.5. Relaxation times

During the discussion of the compression tests, it was pointed out that there are several phases during the deformation. The sample does not return to its original state instantaneously during the decompression phase. This residual deformation varies with the speed of solicitation applied to the samples. It is necessary to let the samples break for a certain period to recover their initial shape.

Relaxation times are found to have a linear correlation with the foam density, and they are sensitive to foam porosity, since the higher relaxation times occur with the larger pore diameters and higher porosity which is the soft polyurethane foam.

The increase in pore size in the soft foam also leads to a decrease in the time required to reach the maximum recovery plateau, this finding has also been confirmed in previous studies [21,26].

As can be seen in the literature, the viscosity response to the deformation is related to the time, and thus this test showed that the slowest relaxation time occurred with the hardest foam, which has the highest viscosity compared to the soft and medium foams. Fig. 7 compares the recovery time of the three densities for a holding time of about 20 min.

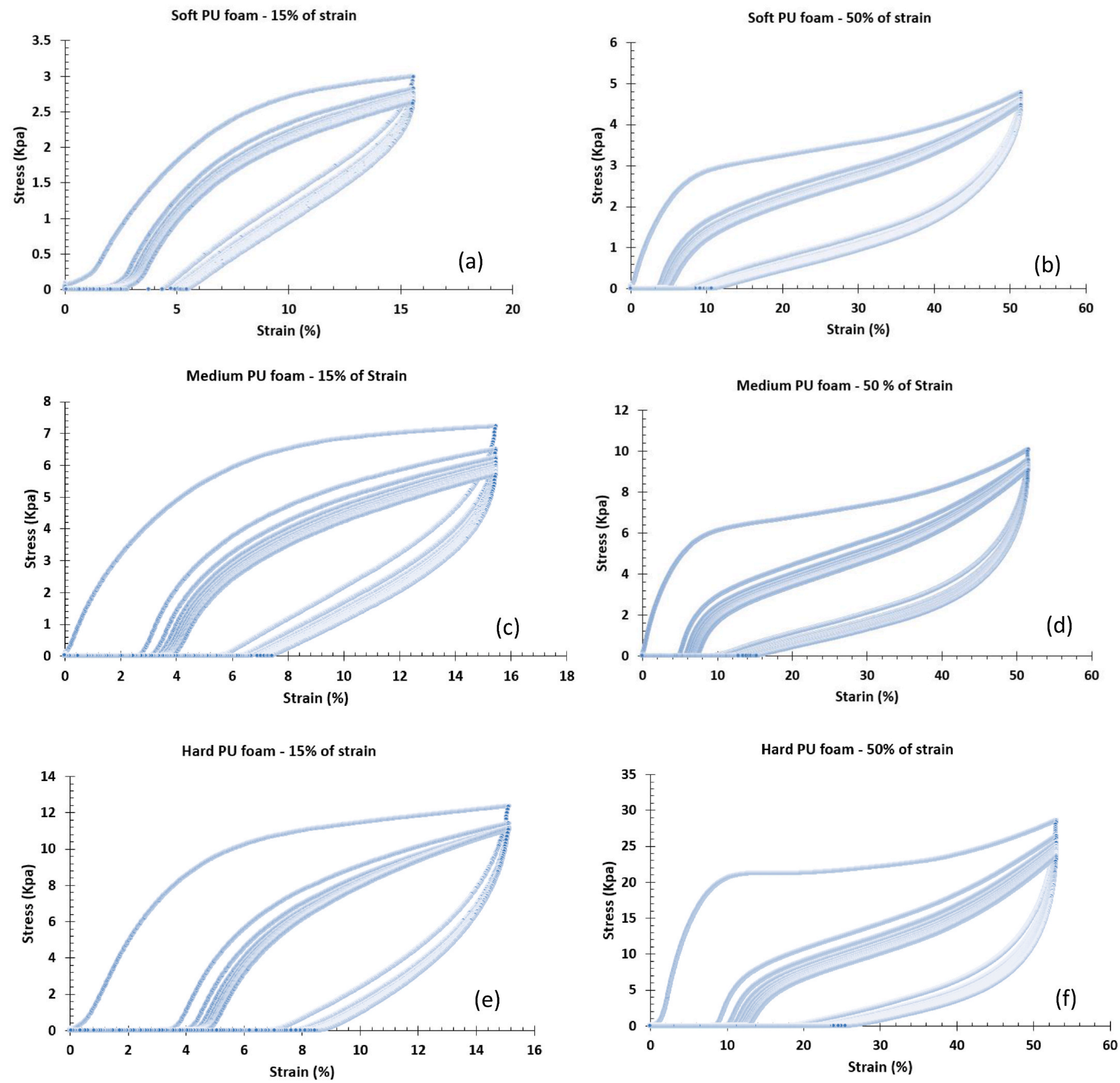

Fig. 4. The cyclic loading stress-strain curves at various strain amplitudes (a,c,e) 15%, (b,d,f) 50%.

An obvious observation is that polyurethane foams do not react in the same way for different densities, even if their cross-linking rate is identical.

As conclusion for this essay. The slowest relaxation time at 50% of deformation happened with the highest viscous behavior, which is the property of the hardest foam. Soft and medium foams have a fast relaxation time because they have a lower viscous behavior than the harder ones and have a larger pore diameter than hard foam. This means an inverse relationship between relaxation time and pore diameter.

4.6. The performance of polyurethane foam as pressure relief in pressure ulcer management/prevention

According to literature, the limit of the interface pressure (the pressure in the contact point body/external support) is 4.26 kPa (32 mm mercury), this energy is called the limit energy, above this energy, a blood occlusion can take place and the risk of having a pressure sore is high [27]. In other words, the damper, which is the mousse of polyurethane in our study, should keep the residual interface energy below 4.26 kPa (32 mm mercury).

Since the interface pressure is related to the weight of the member and the exterior support (hospital mattress), it is crucial to choose the appropriate density of the polyurethane foam (soft, medium, hard) to be able to apply it to the target part of the body (heel, sacrum, elbow). For example, the literature reported interface pressure for the heel at a position of 60° on a standard hospital mattress is 6.6 kPa (50.15 mm mercury) [28]. In this case, the soft polyurethane foam is recommended to use because this foam can dissipate 41% of energy at 50% of foam compression as ideal performance (table A. 3), which mean it remains 2.7 kPa (20.25 mmHg) of residual energy at interface contact

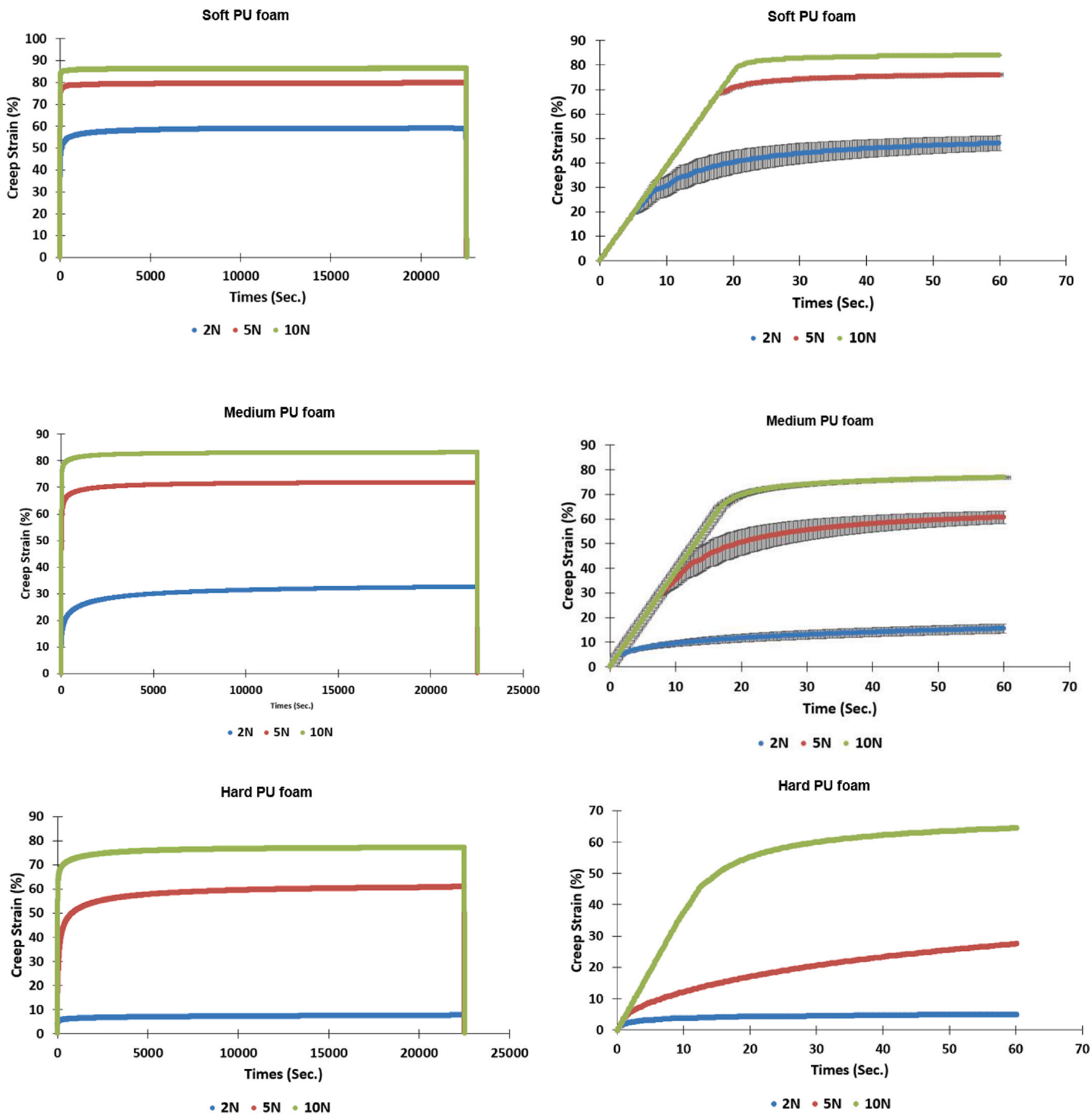

Fig. 5. Creep test for 6 h with different constant stress (2, 5 and 10 N) exerted on soft, medium and hard foam of polyurethane.

(body/support) which is inferior to the interface pressure limit 4.26 KPa (32 mm Hg).

By applying this calculation to several clinical situations, the choice of foam density can be made according to the energy to be dissipated. Some examples (table A. 4).

5. Conclusion

Supports are recommended for the prevention and treatment of pressure ulcers as part of a comprehensive strategy. This study evaluated the viscoelastic behavior of three densities of polyurethane foam, measuring both the damping and softening effects. Compression tests showed the foam's pressure relief performance, while creep tests indicated its viscous behavior and stability. The foam's dissipation coefficient (DE) determined energy dissipation, suggesting harder foams for heavier body parts, and the medium or soft foam can be used for the lighter member. Cyclic softening and relaxation times were observed, revealing the softening behavior and strain-dependent behaviors. Foam density correlated with viscoelastic properties, affecting the damping effect. While supports are effective, they do not replace traditional preventive measures (fight against malnutrition, mobilization, treatment of general pathologies) and careful monitoring of at-risk areas.

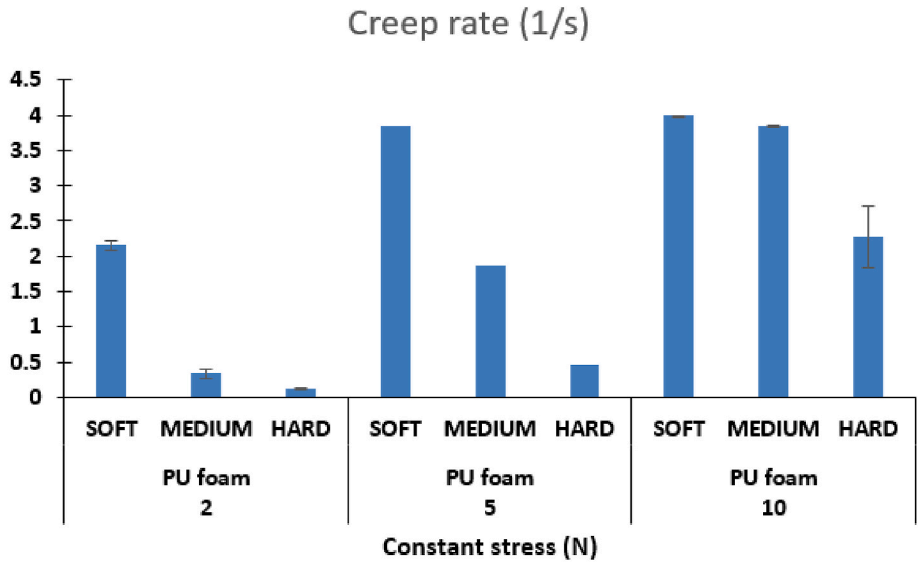

Fig. 6. Creep rate with different constant stress for the three different densities of polyurethane foams.

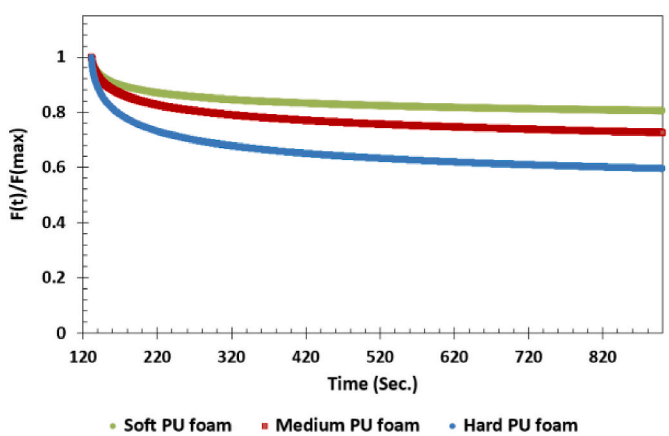

Fig. 7. Stress relaxation behavior of polyurethane foam hard (blue), medium (red) and soft.

Credit author statement

Abdullah Mouchati: Conceptualization, Methodology, Writing – original draft. Salah RAMTANI: Writing- Reviewing and Editing. Najet YAGOUBI: Writing- Reviewing and Supervision.

Table A.1
pore's area and percentage of open porosity for the three hardness of polyurethane.

Foam Polyurethane	Pore's area (nm)	Percentage of open porosity
Polyurethane Soft	909.1 ± 124.653	36.94%
Polyurethane Medium	440.46 ± 54.072	34.26%
Polyurethane Hard	122.852 ± 146.4	22.21%

Table A. 2
Evolution of Young's modulus in three different densities of polyurethane foams

Sample	0,1 mm/s	1 mm/s	10 mm/s
	Compression Modulus (MPa)	Compression Modulus (MPa)	Compression Modulus (MPa)
Soft	20,99 ± 2,64	31,41 ± 5,36	55,16 ± 3,89
Medium	37,33 ± 1,74	65,05 ± 11,14	145,09 ± 23,51
Hard	182,88 ± 16,95	290,03 ± 77,63	644,78 ± 77,78

(continued on next column)

Table A. 2 (*continued*)

Table A. 3
Energy dissipated by PU foams

PU foams	Strain (%)	Dissipation coefficient DE (%)
soft	30	38,67 ± 0,59
	50	41,19 ± 0,21
	70	47,50 ± 1,73
Medium	30	49,06 ± 0,32
	50	49,59 ± 0,65
	70	52,70 ± 0,05
hard	30	68,08 ± 0,73
	50	71,85 ± 0,37
	70	68,73 ± 1,21

Table A. 4
the choice of foam hardness according to the energy to be dissipated.

Soft PU foam	Medium PU foam	Hard PU foam
Heel at a position of 60° and 90° on an anti-pressure foam mattress [28]	Elbow on a foam mattress (Clinifloat) (Allen, Ryan, et Murray 1993)	Sacrum, heel on a foam mattress (Clinifloat) (Allen, Ryan, et Murray 1993)
Heel in medium pressure on a bed (Do et al., 2016)	Heel at a position of 60° on a standard hospital mattress [28]	Sacrum, heel at a position of 90° on a standard hospital mattress ([28]; Do et al., 2016; King et Bridges 2006)
Sacrum in medium pressure on a bed (Do et al., 2016)	Sacrum on a standard mattress (Do et al., 2016)	

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Abdullah MOUCHATI reports financial support was provided by Novomed Group. Abdullah MOUCHATI reports a relationship with

Novomed Group that includes: employment.

Data availability

No data was used for the research described in the article.

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