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Quasi-Static Compression and Microstructural Characterization of Polyurethane Foams for Potential Use in Shock Absorbers

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Abstract:

This study focuses on the detailed characterization of modified polyurethane foams, emphasizing their quasi-static compression behaviour and microstructural properties, to evaluate their potential application in shock-absorbing systems. Through systematic synthesis, we produced various formulations of polyurethane foams. We subjected them to comprehensive quasi-static compression tests to understand their deformation and energy absorption characteristics under controlled loading conditions. Concurrently, microstructural analyses were conducted to elucidate the relationship between the cellular architecture of the foams and their mechanical responses. Although the foams were not directly integrated into shock absorbers, the findings lay a foundational understanding of how their structural and compositional variations influence performance metrics crucial for shock absorption applications. This research contributes to the broader knowledge base required for the future design and optimization of polyurethane foam-based shock absorbers, highlighting critical areas for further investigation and development.

1. INTRODUCTION

Many researchers studied foam behaviour, using different methods to form their responses. Ashby and [1] studied single-cell behaviour in a micro-mechanical system to explain the mechanical characteristics of cellular substances. The foam was cellular cubic. Warren and Kraynik [2] saw open cells as the tetrahedral norm. Zhu *et al*. [3] identified Kelvin's high foam compression deformation. Thus, micromechanical approach models provided strong results for predicting mean elastic behaviour. Continuum mechanics can also depict mechanical foam behaviour, and the method ignores sample size [4]. This strategy is helpful since it incorporates several loading scenarios into a single model. Using finite elements to analyze foam reaction by Ogden *et al*. [5], Blatz and Ko [6], and Yeoh and Truong [7]. It can be utilized for hyperelastic flexible foam and microscopically homogenous deformation. These models focus on studying energy deformation, and stress formulation introduces strain energy centred on the gradient fracture.

Polymer foams are commonly used, for example, in-seat covers, cups, coffee overlays, and supplies for packing [8]. The use of foam involves isolation, weight reduction, booming, redistribution of energy, and tension for several purposes. Most materials can be used to create foam [9]. Microcellular foams are a recent development [10] to minimize the quantity of materials used in production. These foams can be as little as 10 µm in cell diameter. Including other polymers, including polyurethane foams, are viscose elastic foams [9]. The foam structure is formed [11] initially by saturating a non-reactive gas sample in a stressful environment, CO_2, and then reducing environmental pressure to support nucleation and microcell formation. The strength or rigidity of the foam does not depend on the cell width only [13]. However, developing a foam structure can boost specific characteristics [12], leading to variations in the solid matrix. Polyurethane foams are available for packaging, coating, and sports equipment in many densities [14]. Polyurethane foams are used to prevent and lower pad ulcers in case of falls [15, 16]. Due to its low cost and low density, polyurethane foam is a significant cellular substance utilized in different technologies due to its simple forming and outstanding energy-absorbing properties [17]. Viscoelasticity is a fascinating aspect of foam mechanics. It combines viscous liquid with elastic solid [18].

Non-lethal projectiles hinder and incapacitate people in situations such as riots, crowd control, and suspicious sea vessels' interception [19]. They offer an alternative for an adequate response by guaranteeing neutralization without causing permanent injury to the intended targets. There are a whole host of products on the market. However, no study has been carried out beforehand to link the material's properties to the injury levels caused by these projectiles [4]. Indeed, various cases have reported severe injuries, even death, following the use of this type of projectile. Therefore, it is essential to associate the manufacturing process with assessing the injury risk of these projectiles to avoid any situation contrary to the doctrine of the use of non-lethal projectile weapons [20].

Due to their adaptability, polyurethanes have been employed in various applications [21]. The market achieved world consumption figures of around 8.5 million tonnes in 2000. Utilization efficiency du mater is essential for reliable material properties and behaviour knowledge. When a structure material's qualities are unknown or misrepresented, there will be potential misuse and catastrophic, with dangerous consequences. Polyurethane foams have fascinating characteristics for several wide uses [22]. The characterization of the behaviour of these foams given a particular use cannot, therefore, be done without the knowledge of the application, namely the target mode of stress. This knowledge will make it possible to define the deformation mechanisms from a laboratory test campaign as a representative.

Rigorous mechanical testing must be performed to understand better the foam's behaviour under common structural loading scenarios. The type of test was made according to the mechanical stresses undergone during use. Foams, in general, are subjected to compressive forces. Mechanic tests are generally used at the industrial level during the quality control procedure. The mechanical characteristics of the material leaving the production line are thus verified. The most frequently used test methods for analyzing flexible cellular material are standardized in ASTM D3574 [23, 24]. This standard contains the methods of preconditioning foam samples and the description of analytical procedures for analyzing physical properties such as density, tensile strength, tear strength, airflow, resilience, compressive strength and permanent deformation.

Synthetically, cellular polyurethanes are made by reacting polyisocyanates with polyols. This class of polymers can lead to flexible rigid or semi-rigid foams depending on the composition and structure of the

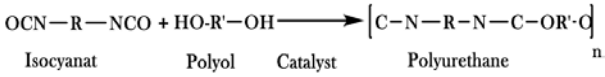
reagents used. In this work, we propose a study on the behaviour of polyurethane foam with open porosity under quasi-static compression. Flexible, open-cell polyurethane foams are often exposed to condensation and monotonic load, based on which compression tests have been chosen for the load change as a displacement function [25].

Using foam materials in energy-absorbing structures has garnered considerable attention in recent research, particularly in enhancing such systems' impact resistance and energy dissipation capabilities. Notably, the dynamic response of sandwich plates, which incorporate GLARE face sheets and a honeycomb core, has been extensively studied when subjected to impacts by metal foam projectiles. These investigations have provided valuable insights into the mechanical behaviour and resilience of foam-based composite structures under high-velocity impacts, highlighting the potential of foam materials in improving the impact performance of energy-absorbing systems [26]. Furthermore, comprehensive reviews on sandwich structures under impact loadings have shed light on these materials' experimental, numerical, and theoretical analyses. Such studies underscore the critical role of foam and other lightweight core materials in enhancing the structural integrity and energy absorption efficiency of sandwich composites under various loading conditions, thereby contributing to the advancement of protective and energy-dissipative technologies [27].

2. EXPERIMENTAL METHODS

2.1. Elaboration of Polyurethane Foams

Polyurethane formation consists of several ingredients and two or three simultaneous responses, as shown in equation (1). The reaction occurs in a combination of urethane isocyanate and polyol in the corresponding reaction equation. The polymer is blown to create a polyurethane foam by forming carbon dioxide using auxiliary reactive chemicals, which vaporize to supply additional gases to the liquid [28].



(1)

Free expansion of the PUR and optimal formulation were first performed in small beakers under low stirring speeds of 1000 rpm. Mixing can also be made from solutions; all formulations are summarized in the six main formulations. After each step, the formulation is corrected based on the appearance of the foam obtained. Additives are materials added to a polymer to modify its properties or characteristics. Some additives included in the polyurethane foam are in the following Table **1**:

The preparation of the PUR is in free expansion mode, that is, at atmospheric pressure using a reactor with a volume of 300 ml, then mixing the reaction combination using a mechanical stirrer reaching a speed of 2500 rev/min. After thickening the PUR and cooling, it is removed from the mould. By reproducing it in a larger Teflon beaker, we end up with a foam that appears in Figure **1**.

Polyurethane foams develop new materials with better properties than the primary constituent polymers. Each polyurethane foam manufacturer jealously guards its recipe for the main components, petroleum-derived (polymers) such as polyol and isocyanate, and catalysts. Because the mixture of polyurethane foam components and catalysts is first emulsified and spread in thick layers on a conveyor belt, this liquid layer rises like bread dough. The chemical reaction produces an intense heat release. The water vapour increases by its lightness, and its pressure increases. The expansive or swelling effect of the dough, which thus becomes more and more spongy. There are, of course, several recipes

Table 1: Some Additives Included in the Polyurethane Foam

Samples	Polyol (g)	PMDI (g)	Catalyst (g)	Glycerol (g)	Silicone (g)	Bentonite (g)	Dichloromethane (g)	PEG (g)	Alumina (g)
PU_1	100	51.61	1.48	2.21	1.32	0	1.19	2	0
PU_2	100	42.09	2.11	3.71	3.51	17.81	0	0	0
PU_3	100	44.94	2.14	3.68	2.5	17.84	0	0	0
PU_4	100	47.44	1.57	3.69	2.48	5.66	0	0	0
PU_5	100	40.88	23.22	3.77	2.11	0	2.11	0	1.2
PU_6	100	40.36	2.64	1.54	4.17	0	1.24	1.6	0

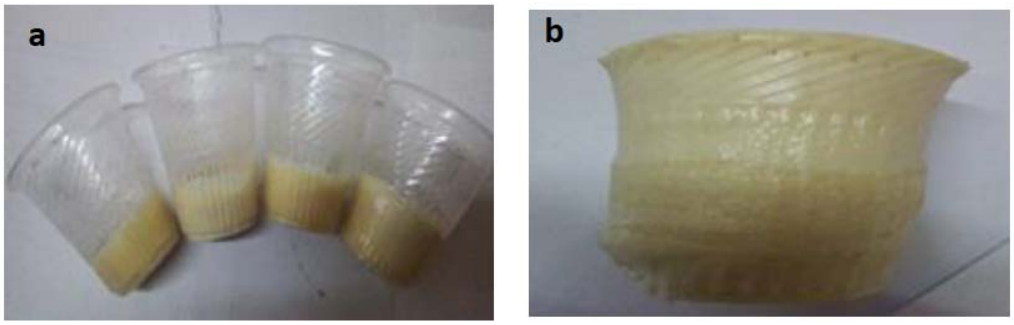


Figure 1: a) Evolution of the samples. **b**) The final shape after 24 hours.

and, therefore, several types of polyurethane foams. The manufacturing process is the same. Only the characteristics desired by the manufacturer (density, elasticity, resistance) determine the dosage of the mixture. Polyurethane foam is more spongy, with giant cells allowing better air circulation. The work methodology flowchart is shown in supporting information SI.

A cell control or surfactant typically adjusts the mixture's viscosity and surface tension to ensure that formed gases are trapped. And that the bubbles are generally of the same size, retained. Some silicone oils are commonly used as surfactants. Catalysts monitor the beginning and reaction rates leading to the polyurethane polymer. As a result, two or more catalysts are often needed. Even if water is applied to the solution to induce moisture, a catalyst favouring a water isocyanate reaction is appropriate. Isocyanate and polyol are typical reactions if the above materials are appropriately combined. The result is called urethane. Many such groups are formed to create a polymer network function. The final polymer stiffness is the average chain-to-chain relationship (Cross-link density) and urethane distance. The shaped gas quantity defines the density of the foams.

The final properties of polyurethane foam depend on the chemical components, the blowing agent, the process conditions, and the mould facings' nature. Thanks to the constant development of new formulations, polyurethane foams with various textures and hardnesses are manufactured today. Several test pieces were made based on different formulations. Six series of test specimens are devoted to the compression tests in two different cutting directions, i.e., the cutting of the foam blocks into test specimens is carried out in the vertical and horizontal directions (Figure **2**). This medium was used to demonstrate the effect of varying machining orders on the mechanical behaviour of static compression.

2.2. Mechanical Characterization

2.2.1. Compression Tests

Six different sets of samples were compressed. Each series consists of four identical cylindrical test pieces made using established recipes. The specimens are squeezed to a predetermined distortion between the apparatus's two compression plates. A force sensor measures and records the variation in the stress applied to distort the sample. Data analysis visualizes stress values against strain values to show the stress-strain curve (Figure **4** in **SI**). The apparatus used for the compression tests is a 40 T dynamometer used in tension and compression (Figure **2** in **SI**).

The mechanical compression tests were performed according to standard ASTM D3574 [29]. This test involves compressing the sample to 80 % of its specific thickness at a 2 mm/min displacement speed. Compression is maintained for 900 seconds. After sixty seconds, the stress-strain curve and the final stress value are recorded as compressive strength. According to Hooke's law, the acquisition software calculates the value of Young's modulus (E), where is the measured stress and is then applied and recorded strain. The machine is controlled by a computer using the Merlin software, which allows the design of complicated cycles and the piloting of experiments with varying speeds in force or displacement. According to Harte *et al*. [30], it is recommended to use engineering constants when analyzing the stress-strain response of foams, even up to enormous strains. For this purpose, we measured each test piece's dimensions just before the test.

2.3. Microstructural Characterization

We coat the samples with gold material using a vacuum system suitable for SEM analysis. The cavity was forced back under 50 mTorr during sputtering and then babbled under the stress of about 75 mTorr using

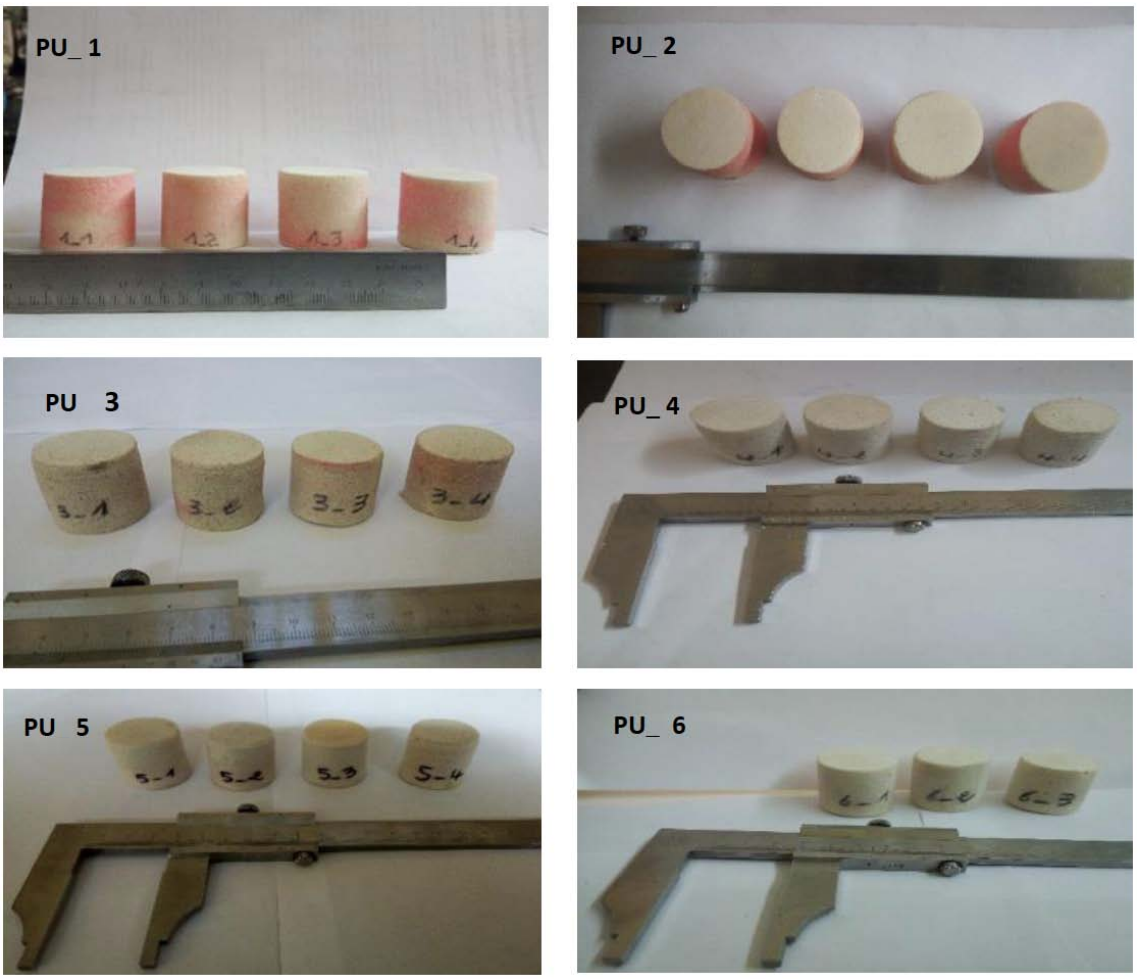


Figure 2: A range of test specimens were manufactured on the polyurethane foam formulation.

an argon gold target. The sample was then placed into the transmission electron microscope Jeol JSM-6100 to check.

2.3.1. Optical Microscopy

Morphology analysis has been performed using an OPTO-EDU A12.1502-T accelerated material trinocular optical microscope. Due to the three-dimensional structure of foams, optical microscopy depth limits imply that modest magnifications are appropriate.

2.3.2. Scanning Electron Microscopy (SEM)

Images were acquired using an SEM by Jeol JSM-5410LV linked to an Isis Energy-dispersive X-ray spectroscopy (EDS) and an EMA probing Oxford Link. The SEM was employed with a voltage value 10KV in a high vacuum HV. Using a sharp blade, cut foam samples into about 5x3x2 mm pieces. Each item was a sample holder made of aluminium. Gold plating is necessary to provide a conductive layer on the specimen surface, preventing charge buildup.

3. RESULTS

3.1. Compression Tests

The characteristic force-displacement curve of polyurethane foam (Figure **3**) shows the three strain regimes typical of viscoelastic materials. The first part of the curve is linear and corresponds to the elastic regime. Upon removing the stress, the strain of the sample is completely reversible. After the yield point corresponds to the linear part's end, the stress-strain curve shows a long plateau at almost constant stress. This part corresponds to the plateau regime.

It causes structural deformation and cell wall rupture in the case of polyurethane foam. As the strain increases, the cell walls come into contact. When all the voids are filled, the strength of the foam increases rapidly, in proportion to the measured stress. This latter part of the curve is known as the densification regime. According to Gibson and Ashby's classical theory of foams [31], the representative curve of the

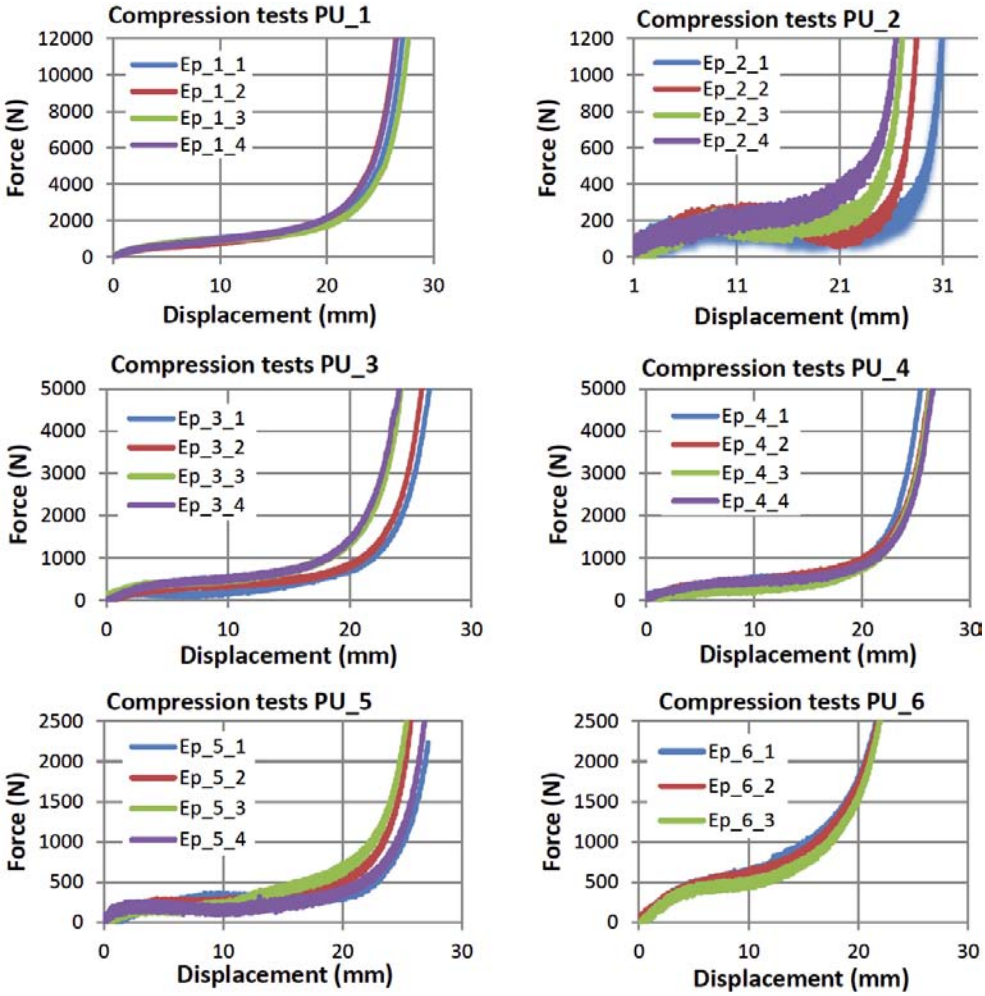


Figure 3: The characteristic force-displacement curve of polyurethane foams.

compression of cellular solids, whether plastic or elastomeric, demonstrates a phase of linear growth followed by a plateau of the load (force) and at the end, a phase of densification where the load increases considerably with displacement. This three-stage behaviour also agrees with the work of Goussery-Vafiadès [32]. The force-displacement behaviour of polyurethane foam consists of three phases.

A slight dispersion is observed between the six test pieces under manufacturing and testing conditions. They agree with the work of Bezazi and Scarpa [33], except that the maximum force obtained by the latter is more than double for the same loading rate, i.e. 80%.

Polyurethane foams' mechanical qualities rely on their density, cell structure (size and shape), and a fraction of closed and open cells. The foam may have a preferential orientation in the form of the cells. Cells frequently appear elongated along the direction of expansion. The yield strength of foam rises with density [34, 35] while the elongation of the platen decreases [36]. Writers mean that a high-density foam withstands the applied stresses better than a low-density foam. However, the structure of a high-density foam achieves the densification regime at low strains. For rigid foams, instead of observing an increase in stress due to densification, the stress value decreases sharply at the end of the plateau. When the cell walls rupture, the foam structure collapses [37].

Found that adding bentonites or alumina particles more diminutive in size than the foam cells increases the value of the initial modulus in the stress-strain curve. On the other hand, if the dimensions of the added particles are larger than those of the cells, the reinforcement is ineffective [35]. Polyurethane foams consist of a mixture of rigid domains and soft domains. It has been found that increasing temperature or humidity significantly deteriorates the mechanical properties of foams [38]. This loss of mechanical properties corresponds to a decrease in compressive

Table 2: Characteristics of Samples before and after Compression Tests

Samples	Tests	Length (mm)	Length after compression (mm)	Diameter (mm)	Diameter after compression (mm)	Density (g/cm^3)	Density after compression (mm) (g/cm^3)
PU_1	PU_1_1	35.6	30	35.5	31	0.32	0.5
	PU_1_2	35.5	30.5	35.7	33	0.34	0.46
	PU_1_3	35.5	30	36.5	33	0.31	0.45
	PU_1_4	35.4	30	35.9	33.2	0.32	0.44
PU_2	PU_2_1	34.72	34.41	34.2	32.61	0.07	0.08
	PU_2_2	32.5	32.41	32.41	33.22	0.08	0.07
	PU_2_3	30.72	30.42	34	32.34	0.07	0.08
	PU_2_4	30	30	31.51	30.3	0.07	0.079
PU_3	PU_3_1	32.31	32	32.71	32.5	0.23	0.23
	PU_3_2	31.68	32.31	31.6	31	0.23	0.24
	PU_3_3	30.01	30	32	32.71	0.24	0.22
	PU_3_4	30.4	30	32	33	0.27	0.26
PU_4	PU_4_1	32.36	32.1	32.4	32.66	0.23	0.23
	PU_4_2	32.48	32.16	32.58	33	0.23	0.22
	PU_4_3	32.58	32	32.6	33.1	0.23	0.22
	PU_4_4	32.3	31	32	32.58	0.22	0.23
PU_5	PU_5_1	33.16	32.56	33.1	33.06	0.16	0.16
	PU_5_2	31.18	30.4	31.78	33.28	0.18	0.17
	PU_5_3	31	30.42	31.4	33.1	0.18	0.17
	PU_5_4	32.66	32	32.1	32.94	0.17	0.17
PU_6	PU_6_1	32.58	32.18	32.66	33.56	0.34	0.32
	PU_6_2	33.64	33.28	33.14	34	0.32	0.31
	PU_6_3	35.6	32	32.48	33.36	0.34	0.32

strength. It is probably linked to splitting chains belonging to the rigid domains (urea and urethane bonds) and the breaking of hydrogen bonds [39].

Determining the apparent density (p) of the different polyurethane foams studied consists of weighing the samples by an electronic balance with an accuracy of 0.01 g and calculating the volume of the test pieces. The average results obtained for polyurethane foams are presented in Table **2**:

3.2. Microstructural Characterization

3.2.1. Optical Microscope

Figure **4** illustrates the findings of the microstructural characterization of the polyurethane foams employed as reference material. The optical microscope picture depicts a partly open-cell foam that is not entirely closed by its wall and communicates with neighbouring cells or outside. Cell walls are visible between the two divisions of specific cells. However, the vast majority of cells lack membranes. In general, open-cell or partly open-cell foams are semi-flexible or flexible materials. The partially open cellular structure is consistent with the foam's soft nature in this scenario.

3.2.2. Scanning Electron Microscopy (SEM)

The structure of these foams changes significantly depending on their density value. Figure **5** shows SEM images of semi-open microcytic clusters for six samples of varying compositions. Microstructures of foam detection, square specimens of 8 mm coupled were randomly taken off the foam pieces in the trio space orientation. The SEM review contributed an estimate of the mean cell measurements. The scope of these granules and cells changes under the cross-section.

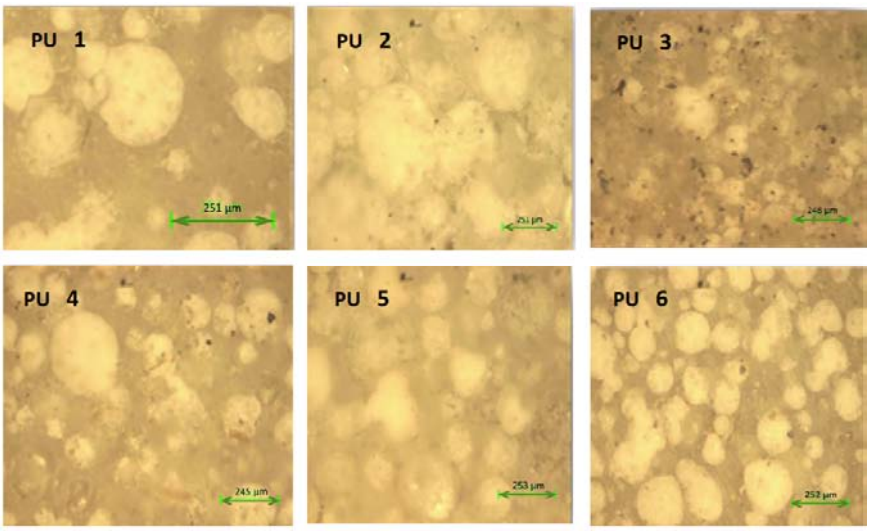


Figure 4: Cellular image of polyurethane.

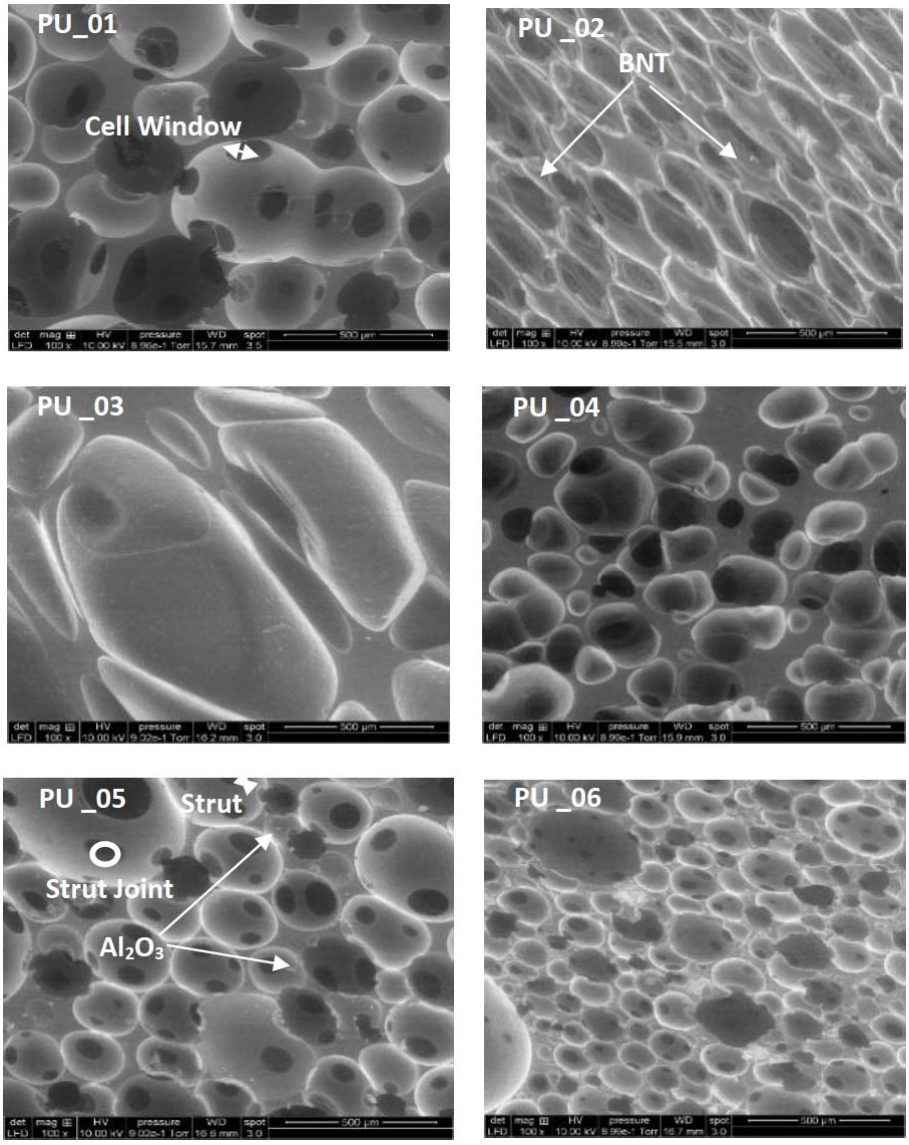


Figure 5: SEM photomicrographs of the polyurethane foam microstructure of manufactured samples.

Indeed, it can correspondingly be observed that one standard discrepancy in cell edge distribution is more significant for foams containing loads such as bentonite and alumina. These volume samples are statistically composed of 1500 grains and even some closed cells, which cannot be considered an initial representative size of half-open foam [40]. For static tests by uniaxial compression, it can also be supposed that the haphazard organization of cells in the cross-linking of the foam formulations does not show any particular orientation in the cell microscopes. Several studies have investigated and examined the principle of foaming behaviour and properties through initial stress tests [41].

It is evident from electronic scan images that the porosity of the foam determines the compressive power: the less porosity, the more significant the residual impact. For example, the foams PU 02 and PU 05, which contain high porosity, respectively, produce fast responses with residual viscoelastic effects. In contrast, foams PU 01, PU 03, PU 04, and PU 06 with minor porosity respond to residual stress effects in the foam. The opposite of the random elastic strength is decreased with the porosity of the mousse by half the vacuum cycle since it is semi-solid and takes time to return to normal.

4. CONCLUSIONS

This study explored polyurethane foams with open-cell structures, emphasizing their potential in shock absorption applications, particularly within quasi-static compression environments. By synthesizing cellular polyurethanes via the reaction of polyisocyanates with polyols, we produced foams with varying degrees of flexibility, rigidity, and semi-rigidity, contingent upon the reagents' composition and structure. Our investigations revealed that these foams exhibit a distinctive three-phase viscoelastic behaviour under compression, encompassing linear elastic deformation, a plateau region, and densification, thereby underscoring their suitability for energy absorption under monotonic loads.

The microstructural analysis corroborated the open-cell nature of the synthesized foams, which is crucial for their application in energy-dissipating systems such as shock absorbers. Future work will extend to dynamic compression tests to further elucidate the foams' performance under impact conditions, a critical factor for their intended applications.

The refinement of the production process emerged as a necessary step to enhance the reproducibility and consistency of the foam characteristics, which is vital for ensuring the reliability of these materials in practical applications. The ultimate aim of this research was not only to develop polyurethane foams with optimized mechanical and microstructural properties for impact resistance but also to contribute to the broader field of materials science by providing insights into the design and characterization of cellular polymers for energy absorption.

This body of work holds significant implications for developing lightweight, efficient shock-absorbing materials, with potential applications extending beyond the scope of this study to include various industrial, automotive, and safety-related domains. By advancing our understanding of polyurethane foam behaviour under quasi-static and, prospectively, dynamic loading conditions, this research paves the way for innovative solutions to enhance passive protection systems, catering to civilian and military needs.

CONFLICTS OF INTEREST

The author added that the study was conducted without any business or financial arrangement that can be viewed as a possible conflict.

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AUTHOR CONTRIBUTIONS

Formal analysis, Writing - Original Draft Preparation, Funding acquisition BN; Resources, Writing - Review and Editing, Software, Investigation D.R.-J. Review & Editing, Project administration, Supervision, visualization G.J.-F; Data Curation, Conceptualization and methodology LC. All writers approved the final manuscript.

DECLARATION OF COMPETING INTEREST

The authors state that they have no known conflicting financial interests or personal ties that might have influenced this study.

SUPPLEMENTAL MATERIALS

The supplemental materials can be downloaded from the journal website along with the article.

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