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Evaluating the Mechanical Attributes of Flexible Polyurethane Foam Produced at Various Pressures

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Abstract

This study explores the impact of different pressures (1atm and 0.75atm) on the mechanical characteristics of flexible polyurethane foam, employing varied compositions (0 - 40ppw) of $CaCO_3$*. Foam production occurred under two distinct pressure conditions: vacuum pressure and atmospheric conditions. Mechanical properties, including durability, compression set, resilience, support factor, elongation, hysteresis loss, bounce characteristics (including number of bounces), hardness, thickness loss value, elongation percentage, and tear resistance strength, were quantified using specialized equipment. Results indicate that the foam generated under vacuum pressure (0.75atm) exhibited enhanced bounce characteristics and durability for compositions up to 40ppw of* $CaCO_3$*, in contrast to foam produced under normal atmospheric conditions (1atm) using identical* $CaCO_3$ *compositions. Across various pressures, an optimal combination of value and quality was consistently observed at 0.75atm with 40ppw* $CaCO_3$ *compositions.*

Keywords: Flexible polyurethane foam, vacuum pressure, atmospheric conditions, calcium carbonate, environmental and sustainable foaming process

INTRODUCTION

Flexible polyurethane foams are versatile polymeric materials, which exists in various forms. Various product categories can be manufactured to possess either rigid or flexible properties, including insulation for freezers and refrigerators, building insulation, footwear, furniture, mattresses, vehicle seats, thermal insulation, and packaging materials. The concept of polyurethanes was established by Professor Dr. Otto Bayer in the 1930s. This involves the reaction between liquid isocyanate and liquid polyol resin, resulting in the formation of a porous, cellular-structured synthetic material known as polyurethane foam [1, 2]. Flexible PU foams can be made slab-stock or molding process from either poly ether or polyester polyols. Polyurethane foams find extensive applications in various products such as furniture, seat cushions, mattresses, and acoustic dampers [3, 4]. Inorganic materials like talc, aluminum silica, dolomite, titanium dioxide, and calcium carbonate are commonly incorporated into these foams as fillers. Calcium carbonate has large use in these industries because of its lower cost, non-toxicity, and non-abrasiveness [8, 9].

Flexible polyurethane foam production costs are largely influenced by the price of polyol, which makes up the majority of the materials used in the manufacture of foam and has the ability to produce exceptional mechanical qualities. Polyol can be substituted with appropriate, reasonably priced fillers in the foam. A few important mechanical properties of the foam are negatively impacted by

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specific filler formulations [10–12]. The goal of this study is to reduce production costs by employing the foaming at different atmospheric pressure conditions and achieve sustained mechanical properties of polyurethane foam by examining the effects of various pressures on functionality and structure property correlation of flexible polyurethane foam using varying calcium carbonate compositions (0 – 40 ppw).

The government has restricted the use of certain auxiliary blowing agents like chlorofluorocarbon, trichloroethane, carbon dioxide, methylene chloride, acetone, pentane and water. The Variable Pressure Foaming technique enables the production of foams with different densities without the need for auxiliary blowing agents, the use of which is prohibited in Europe and other countries [13]. This technique offers a compliant and effective method for achieving varied foam densities while adhering to regulatory restrictions on certain blowing agents. The blowing agents that are both highly carcinogenic and ozone-depleting pose significant health and environmental risks. To address this issue, water has been explored as a natural alternative blowing agent. However, attempts to elevate water levels as an auxiliary blowing agent have presented challenges. High water levels lead to a substantial exothermic reaction, resulting in excessive urea formation. This, in turn, complicates the production of flexible polyurethane foams, leading to subpar foam quality and durability, as well as scorching in the foam, potentially posing a fire hazard during the manufacturing process. Moreover, the rapid cooling process necessitates the excessive usage of Toluene Diisocyanate (TDI), contributing to the release of excess TDI vapor into the atmosphere. This release of TDI vapor is a concern due to its environmental impact. Thus, finding alternatives to mitigate these challenges is crucial for both product quality and environmental sustainability [14, 15].

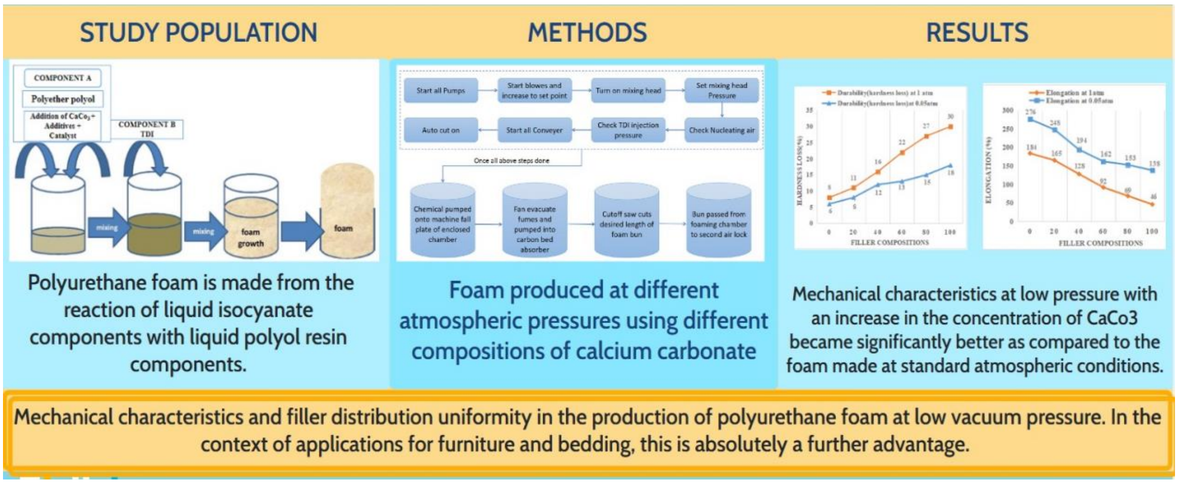
The Variable pressure technique offers a unique combination of environmental friendliness, superior product consistency and unique foam properties. It provides us with a platform for new product technology and a reliable process to meet the increasingly stringent environmental regulations. That gives the foam chemist an extra dimension in creating new products [17, 18].

A novel commercial process for foaming under variable pressure has been successfully developed, showcasing numerous advantages in both pilot operations and commercial applications. The system has demonstrated superior physical properties in the foams produced, with commercial experience attesting to its efficacy. This innovative process opens up the possibility of developing foams that were previously challenging or impossible to produce using conventional methods or under open ambient conditions. In the enclosed chamber, the exhaust is carefully managed by venting it through carbon beds. This filtration process effectively removes TDI (Toluene Diisocyanate) fumes, which are known to be harmful to human health and the environment. By utilizing this system, foams can be produced under vacuum conditions, resulting in a substantial reduction in water levels and TDI usage. This not only enhances the efficiency of the foaming process but also contributes to environmental sustainability by minimizing potentially harmful emissions [16].

Fillers are usually heavy and can settle out of a polyol mixture unless constant agitation is used. It is necessary to determine the fillers according to their nature and incorrect concentration, to obtain a product of particular inheritance and reliable quality. Certain filler compositions may have a negative impact on several important mechanical properties of the foam [20-24].

In the present study, numerous experiments were undertaken, encompassing foaming at both vacuum pressure and atmospheric pressure. Various compositions of calcium carbonate were incorporated as fillers to investigate the impact of different pressures on the mechanical properties of flexible polyurethane foam with a density of 30 kg/m3. The concentrations of the filler ranged from 0 to 40 parts per hundred parts of polyol (ppw). Across all pressure conditions, an optimal combination of value and quality was consistently observed at 0.75atm with a 40ppw composition of $CaCO_3$. Foam produced under below atmospheric pressure (vacuum) exhibited superior mechanical properties, including better compression set, resilience, bounce and number of bounces, durability, support factor, tensile strength, tear strength, elongation-at-break, and reduced hysteresis loss. These improvements were particularly pronounced when compared to foam produced under normal atmospheric conditions with the same 40 ppw composition of $CaCO_3$.

GRAPHICAL ABSTRACT



Polyurethane foam is made from the reaction of liquid isocyanate components with liquid polyol resin components.

Foam produced at different atmospheric pressures using different compositions of calcium carbonate

Mechanical characteristics at low pressure with an increase in the concentration of CaCo3 became significantly better as compared to the foam made at standard atmospheric conditions.

Mechanical characteristics and filler distribution uniformity in the production of polyurethane foam at low vacuum pressure. In the context of applications for furniture and bedding, this is absolutely a further advantage.

Figure

Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

PROCESS SYSTEM OF FOAMING TECHNOLOGY

Process 1: Foaming at Standard Atmospheric Pressure

Foaming has been carried out at 1atm. In this process initially polyol in beaker (component A) was taken, then different compositions of $CaCO_3$ was added and mix it vigorously. Temperature was set on to 20-23°C. Then the required amount of catalyst and water was added in the component A. The solution was mixed with the help of stirrer having speed of 2000 Revolution per minute. Predetermined TDI calculated was taken in the separate beaker (component B). Tin was added in the component A and solution was thoroughly mixed for approx 30 - 40 seconds, then during mixing TDI from Beaker B was added in the component A and mixing was done for around 10-12 seconds. Then solution was poured in the trial box. After full curing of sample (At-least 6-12 hours) the foam was cut in the desired size with the help of normal slitting line (NSL) cutting machine.

Process 2: Foaming at Below Atmospheric Vacuum Pressure

Foaming has been carried out at selected below atmospheric pressure at 0.75atm. The variable pressure foaming system involves producing the flexible polyurethane foam in an enclosed chamber with the vacuum pressure controlled. The vacuum pressure in the chamber is fixed before foaming and remains constant during the foaming operation. Vacuum reservoir with a butterfly valve was used for maintaining the regulating flow of desired vacuum pressure in this process. Initially polyol in a beaker (component A) was taken, then different compositions of $CaCO_3$ was added and mix it vigorously. Temperature was set on to 20-23°C. Then the required amount of catalyst and water was added in the component A. The solution was mixed with the help of stirrer having speed of 2000 rotation per minute. Predetermined TDI calculated was taken in the separate beaker (component B). Tin was added in the component A and solution was thoroughly mixed for 30-40 seconds, then during mixing TDI from Beaker B was added in the component A and mixing was done for around 10-12 seconds. Then solution was poured directly into the trial box. Immediately transfer this box into this chamber, then chamber door is closed so that required vacuum pressure was created in the chamber [12]. After the designated rise and cure time (up to 8 minutes) the vacuum pressure was released and the chamber opened. The sample was then removed. After full curing of sample (At-least 6 - 12 hours) the foam was cut in the desired size with the help of normal slitting line (NSL) machine.

EXPERIMENTAL

Materials Required

Calcium Carbonate(filler) was purchased from Trinity calcium company, New Delhi. The average grain size of the calcium carbonate 10µm. Conventional poly ether polyol was from Dow Chemical, Europe. The product name code is Voranol - 8136. It is a 3000 molecular weight polyol and hydroxyl value is 56. Other materials used are catalysts: Niax stannous octoate (Momentive, USA) and Niax catalyst primary amine B-11 plus, Momentive, USA. The toluene diisocyanate (TDI) used in the study was sourced from BASF company in Mumbai and comprised an 80-20 blend of 2,4 and 2,6 toluene diisocyanate isomers. This particular blend is commonly employed in various applications, including the production of polyurethane foams, due to its specific chemical composition and properties. The surfactant utilized in the study was Niax Silicone L-594, supplied by Momentive, a company based in the USA. This surfactant likely played a role in stabilizing the foam structure during the production process. Distilled water was employed as the blowing agent. The combination of surfactant and blowing agent is crucial in the foaming process, contributing to the formation of the desired cellular structure in polyurethane foam.

Measurements

Variable pressure foaming chamber [Vaccbox, Sheela foam Ltd.] were used for foaming trials. Tensile & elongation properties of polyurethane foams were conducted according to [ASTM D-3574-17, Test E]. The test was carried out using universal testing machine (Hounsfield, H10KS), with a load cell of 50kg and cross head speed of 500 mm/min. The modulus of elasticity, ultimate tensile strength and percentage elongation at break were obtained. In accordance with the ASTM D3574-17 standard, Test B1, the evaluation of the comfort factor of foams was conducted. This assessment focused on the compression modulus and was carried out using a universal testing apparatus as specified in reference [25]. The compression modulus is a key parameter in understanding the comfort characteristics of foams, providing insights into their ability to withstand and recover from compressive forces. The ASTM D3574-17 standard outlines the procedures and guidelines for conducting such tests on flexible cellular materials like foams. Dry aged compression set at 50% compression was obtained according to [ASTM D3574-17, Test D]. This test was carried out at 70ºC for 22hrs. Compression was uniformly applied in a jig designed to compress the foam uniformly and precisely across its entirety. After the 22 hrs. compression, the foams were allowed to recover for 30 min at ambient conditions. The recovered height was then measured, and the compression set value (C_t) was calculated as $C_t = (H_o-H_f) \times 100 / (H_o)$, in which H_o is the original height of the sample, H_f is the final height of the sample.

METHODOLOGY

The methodology for the study on the effects of different atmospheric pressure conditions and various compositions of calcium carbonate on the mechanical properties of polyurethane foam has adopted following steps:

- *Material Selection:* Obtained polyurethane materials with a density of 30kg/m3.Source Toluene diisocyanate (TDI) from BASF, Mumbai, with an 80-20 blend of 2,4 and 2,6 isomers. Used Niax Silicone L-594 from Momentive, USA, as the surfactant. Employed distilled water as the blowing agent.
- *Calcium Carbonate Loading:* Prepare different compositions of calcium carbonate ($CaCO_3$) ranging from 0 to 40 parts per hundred parts of polyol (ppw).
- *Foaming Process:* Conducted foaming trials at two atmospheric conditions: normal atmospheric conditions (1atm) and low vacuum pressure (0.75atm). Utilize a controlled foaming process, incorporating the specified TDI, surfactant, and distilled water.
- *Testing Standards:* Performed mechanical property testing according to ASTM D3574-17[25], Test B1. Measure compression set, resilience, bounce, number of bounces, durability, support factor, tensile strength, tear strength, elongation-at-break, and hysteresis loss.

- *Universal Testing Apparatus:* Used a universal testing apparatus as described in reference for assessing compression modulus and other relevant mechanical properties.
- *Statistical Analysis:* Conducted statistical analysis to identify significant differences in mechanical properties between foam samples produced under different atmospheric conditions and with varying $CaCO_3$ compositions.
- *Data Interpretation:* Analyzed and interpreted the data to understand the impact of atmospheric pressure and $CaCO_3$ loading on the mechanical properties of the polyurethane foam.
- *Results and Conclusion:* Summarized the findings and draw conclusions regarding the optimal combination of atmospheric pressure and $CaCO_3$ composition for achieving desirable mechanical properties in flexible polyurethane foam.

With Calcium Carbonate -Atmospheric conditions (1atm)

Normal foaming process are done in an open atmosphere and the foam also expends against the atmospheric pressure. Trials were done at 1atm with Calcium Carbonate in 30Kg/m^3 density to check how different concentrations of $CaCO_3$ effects the mechanical properties of the flexible polyurethane foam. Temperature of both Raw materials of Polyol and TDI was 20-23 degree Celsius. Formulation sheet was prepared for the trials at 1atm with different compositions of $CaCO_3$ in the (Table 1).

Samples from foam produced were cut into various sizes suitable for their respective test equipment. In this work, varying concentration of $CaCO_3$ ranging from 0 to 40ppw. Physical properties of foam were measured in testing sheet as shown in (Table 2).

Table 1. Fformulation sheet with $CaCO_3$ trials at (1atm).

Chemical Name (ppw)	**Formulations and Concentration of Calcium Carbonate**					
Standard Polyol	69.20	60.12	52.38	46.22	41.76	37.02
Calcium Carbonate	0	12	20	28	32	37
TDI Index	110	110	110	110	110	110
Toluene diisocyanate (TDI)	27.52	25.10	24.63	23.94	23.57	23.27
Blowing Agent	1.94	1.81	1.84	1.83	1.84	1.85
Blowing Catalyst	0.02	0.02	0.02	0.01	0.01	0.01
Gelling Catalyst	0.13	0.11	0.11	0.11	0.11	0.11
Surfactant	1.38	1.20	1.04	0.90	0.81	0.74

*(ppw)- parts per weight**
Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

Table 2. Testing sheet with $CaCO_3$ trials at (1atm).

S.N.	**Testing Parameters**	**Testing standards**	**0ppw $CaCO_3$**	**12ppw $CaCO_3$**	**20ppw $CaCO_3$**	**28ppw $CaCO_3$**	**32ppw $CaCO_3$**	**37ppw $CaCO_3$**
1	Density (kg/m^3)	ISO845	29.22	29.56	30.24	30.55	30.59	30.66
2	Tensile Strength (kg f/cm^2)	ISO1798	1.32	1.01	0.95	0.83	0.70	0.62
3	Elongation (%)	ISO1798	182	164	126	90	68	45
4	Resilience (%)	ISO8307	40	37	34	29	22	20
5	Tear Strength (kg/cm)	ISO8067	0.40	0.34	0.33	0.20	0.16	0.10
	Porosity (cc/sec.cm^2)	ASTM3574[TEST G]	51	48	46	40	38	37
7	CFD (kg f/323cm^2)	ASTM3574[TEST C]	2.60	2.70	2.80	3.00	3.10	3.30
8	Compression set@ 90% compression for 22 hrs							
	Thickness loss (%)	ISO1856	6	9	14	17	22	28
9	Pounding test @20,000 cycles							
	Hardness loss (%)	ISO3385	9	12	18	24	29	31

	Thickness loss (%)	ISO3385	1	1	2	2	2	3
10	Hysteresis loss (%)	ASTM3574 [TEST N]	10	12	18	20	24	27

Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

With Calcium Carbonate – Below Atmospheric Pressure (0.75atm)

Foaming was done at selected pressure vacuum at 0.75atm to produce the foam of 30 kg/m^3 density. Trials were done in foaming chamber which was a closed pressure vessel where the foam formation occurs. Trials were done at 0.75atm with calcium carbonate in 30 kg/m^3 density to check how different concentrations of $CaCO_3$ effects the mechanical properties of the flexible polyurethane foam. The temperature of both raw materials of polyol and TDI was maintained at 20-23 degree Celsius. The formulation sheet was prepared for the trials at 0.75atm with different compositions of $CaCO_3$as shown in (Table 3).

In order to facilitate testing with different equipment, foam samples were cut into various dimensions. The formulation for this study was adjusted to incorporate different concentrations of calcium carbonate (CaCO3), spanning from 0 to 40 parts per hundred parts of polyol (ppw), as outlined in Table 3. This modification allowed for a comprehensive exploration of the mechanical properties of the foam across a range of CaCO3 concentrations, enabling a thorough investigation into the effects of these variations on the material's performance. Physical properties of foams were measured. Testing sheet of selected foam samples is given in the (Table 4).

Table 3. Formulation sheet with $CaCO_3$ trials at (0.75atm).

Chemical Name (ppw)	**Formulations and Concentration of Calcium Carbonate**					
Standard Polyol	72.88	62.08	55.04	47.74	44.30	40.20
Calcium Carbonate	0	12	20	28	32	37
TDI Index	110	110	110	110	110	110
Toluene diisocyanate (TDI)	24.00	23.00	22.21	21.63	21.17	20.47
Blowing Agent	1.60	1.60	1.60	1.60	1.61	1.58
Blowing Catalyst	0.03	0.03	0.02	0.02	0.02	0.01
Gelling Catalyst	0.04	0.06	0.06	0.06	0.05	0.05
Surfactant	1.45	1.23	1.07	0.95	0.85	0.78

*(ppw)- parts per weight**
Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

Table 4. Testing sheet with $CaCO_3$ trials at (0.75atm).

S.N.	**Testing Parameters**	**Testing standards**	**0ppw $CaCO_3$**	**12ppw $CaCO_3$**	**20ppw $CaCO_3$**	**28ppw $CaCO_3$**	**32ppw $CaCO_3$**	**37ppw $CaCO_3$**
1	Density (kg/m^3)	ISO845	29.21	29.43	30.36	30.15	30.28	30.62
2	Tensile Strength (kg f/cm^2)	ISO1798	0.63	0.67	0.83	0.87	1.04	1.09
3	Elongation (%)	ISO1798	194	174	136	114	108	98
4	Resilience (%)	ISO8307	45	40	42	40	37	35
5	Tear Strength (kg/cm)	ISO8067	0.14	0.16	0.17	0.17	0.18	0.21
6	Porosity (cc/sec.cm^2)	ASTM3574[TEST G]	51	48	46	40	38	37
7	CFD (kg f/323cm^2)	ASTM3574[TEST C]	2.10	2.19	2.34	2.37	2.43	2.67
8	Compression set@ 90% compression for 22 hrs.							
	Thickness loss (%)	ISO1856	5	8	11	13	15	18
9	Pounding test @20,000 cycles							
	Hardness loss (%)	ISO3385	8	10	13	15	17	20

	Thickness loss (%)	ISO3385	1	1	1	1	2	2
10	Hysteresis loss (%)	ASTM3574 [TEST N]	8	10	11	15	19	22

Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

RESULTS AND DISCUSSIONS

It was concluded that as we manufacture the foam at below atmospheric pressure, density will also get decreased because as we apply lower pressure (0.75atm) the foam will rise more so density will decrease. So, when we produced foam in higher altitude destinations, we would get a different kind of expansion because the atmospheric pressure is less. Some physical properties of these samples to be tested are discussed below:

- Density of the foam increases as calcium carbonate content increases. So as the filler loading increases, there was a proportionate increase in the density values at standard atmospheric pressure and below atmospheric pressures.
- On adding $CaCO_3$ at 1atm, there was sharp and sudden decrease in the tensile strength parameters. But at 0.75atm, tensile strength value increases gradually up-to 40ppw. The filler loading impact on the tensile strength is smoother under vacuum pressures.
- In both cases, on increasing the filler, hardness levels increased, the reverse being true for elongation. But the elongation of the foam made at 0.75atm up-to 40ppw is increased. So, it shows the good ability of foam to be stretched.
- On increasing the fillers at different concentration, resilience gradually decreases. But at 0.75atm resilience value is much better as compared to similar filler loaded samples produced at atmospheric pressure.
- Tear strength value decrease sharply as increasing the filler concentration. But at 0.75atm, tear strength of the samples increased. As a result of the modifications made to the formulation, the foam exhibited robust resistance to tearing and shredding. The changes in the composition, particularly the incorporation of varying concentrations of calcium carbonate, played a significant role in enhancing the material's ability to withstand tearing and resist shredding. This improved resistance is a noteworthy outcome of the study, suggesting that the tailored formulation contributes positively to the mechanical properties of the foam in terms of tear strength and durability.
- In both cases, on increasing the filler, the hardness levels of foam increased.
- In both cases, on increasing the filler, compression set values increases. However, the thickness loss of foam produced at 0.75atm was 35 to 40% lower as compare to foam made at 1atm.This is a significant improvement in performance of the filler loaded foam produced under 0.75atm.
- For durability test of the foam, pounding test was done and found the hardness and thickness loss gradually increases at both pressures. But at 0.75atm hardness loss value showed relatively less decrease as compared to the standard atmospheric pressure.
- We set the porosity range constant for the pure and filled foam, so on adding or increasing the concentration of filler, the porosity range was gradually decreases.
- In both cases, Hysteresis loss of the foam increases as calcium carbonate content increases. But at 0.75atm, hysteresis loss value is less. So, it shows a good ability of foam to retain its original firmness properties-in comparison to the foam produced at 40ppw filler loading in atmospheric pressure.

MEASURING PHYSICAL-MECHANICAL PROPERTIES

It was found that the physical characteristics of the flexible polyurethane foams showed improved results with a decrease in the vacuum pressure employing filler up to 40 ppw. Figures 1-5 displays a graph of mechanical and physical qualities against vacuum pressure. Figure 1 depicts the impacts of varied atmospheric pressure (1atm & 0.75atm) and filler compositions on the percentage of elongation at break, whereas Figure 2 depicts the resilience of flexible polyurethane foam under varying atmospheric pressure (1atm & 0.75atm) and filler compositions. Figure 3 illustrates the effects of different atmospheric pressures (1atm & 0.75 atm) and filler compositions on the compression set (thickness loss %) of flexible polyurethane foam, while Figure 4 illustrates the effects of those same factors on hysteresis loss of the foam. Figure 5 illustrates the effects of different atmospheric pressures (1atm & 0.75atm) and filler compositions on the durability test (hardness loss %) of flexible polyurethane foam.

EDS ANALYSIS OF FLEXIBLE POLYURETHANE FOAM

Filler particles were observed in their microstructures of flexible polyurethane foam, which was produced at vacuum pressures. Qualitative spot mode EDS analysis of evaluation revealed composition differences between the filler particles (Figures 6 and 7).

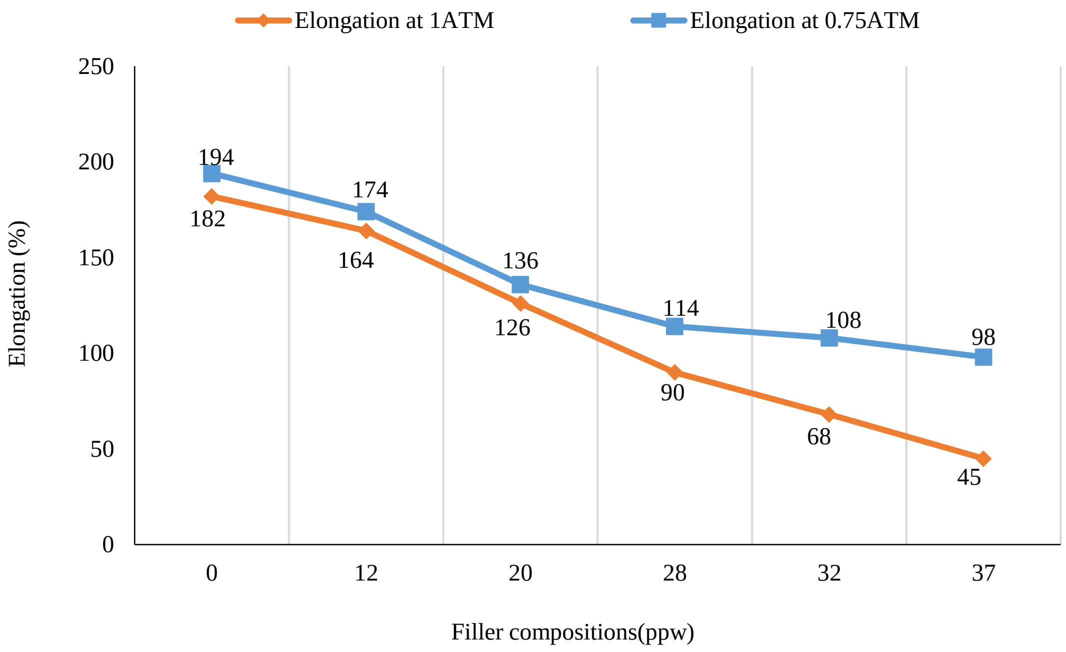


Figure 1. Effects of different atmospheric pressures (1atm & 0.75atm) and compositions of filler on the elongation at break of flexible polyurethane foam.
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

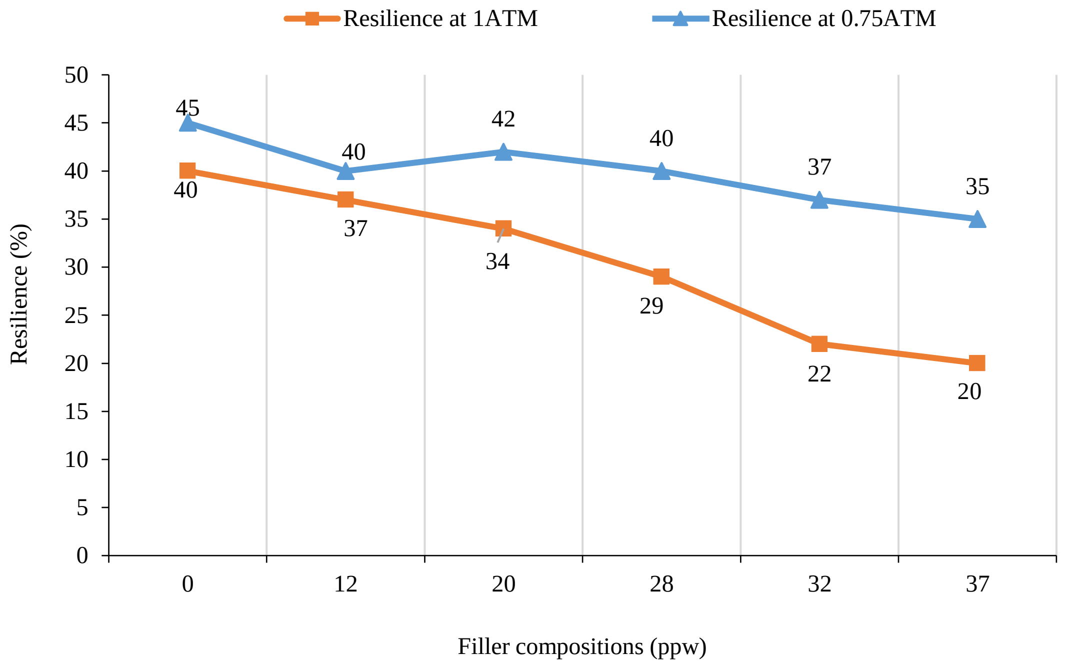


Figure 2. Effects of different atmospheric pressures (1atm & 0.75atm) and compositions of filler on the resilience (%) of flexible polyurethane foam.
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

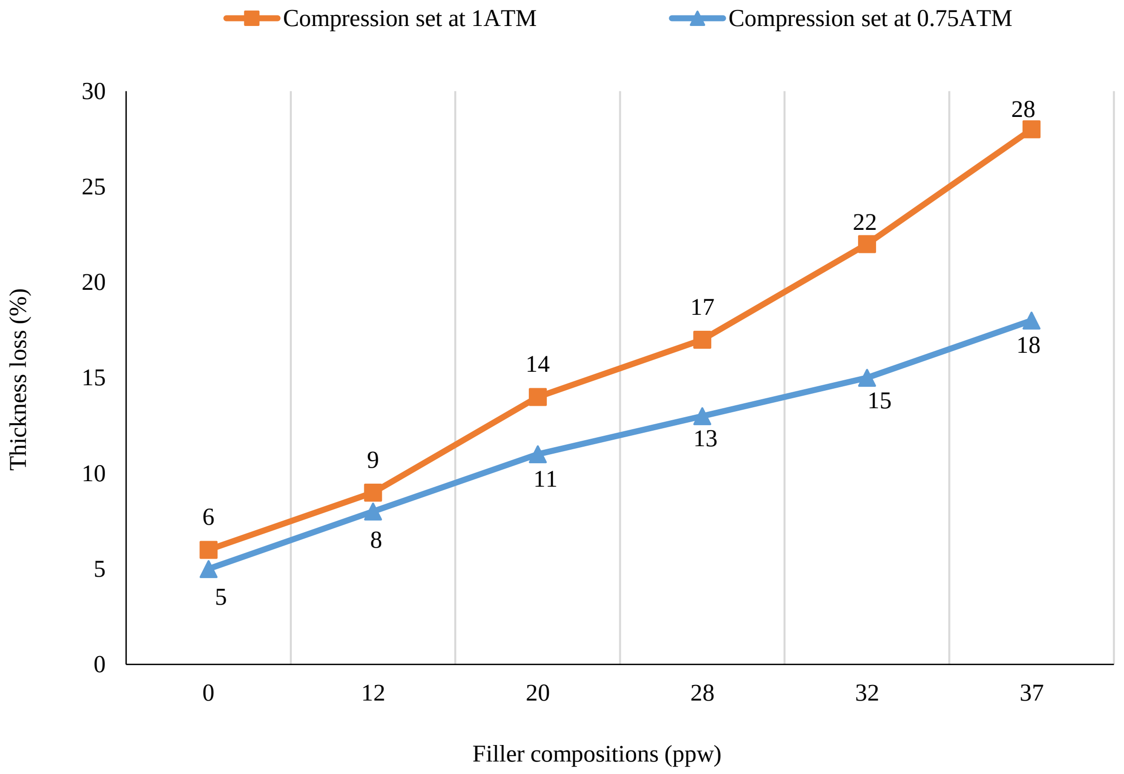


Figure 3. Effects of different atmospheric pressures (1atm & 0.75atm) and compositions of filler on the compression set of flexible polyurethane foam.
Note: *Sourced from self-authored in Sheela foam Ltd. R&D Lab.*

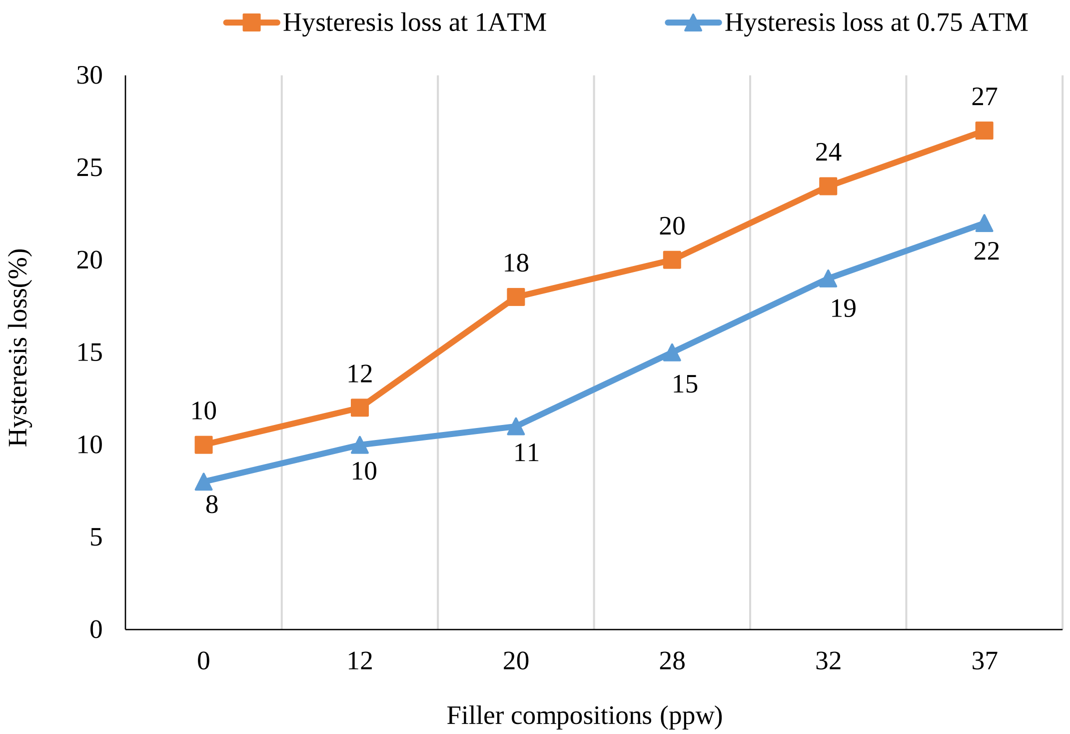


Figure 4. Effects of different atmospheric pressures (1atm & 0.75atm) and compositions of filler on the hysteresis loss of flexible polyurethane foam.
Note: *Sourced from self authored in Sheela foam Ltd. R&D Lab.*

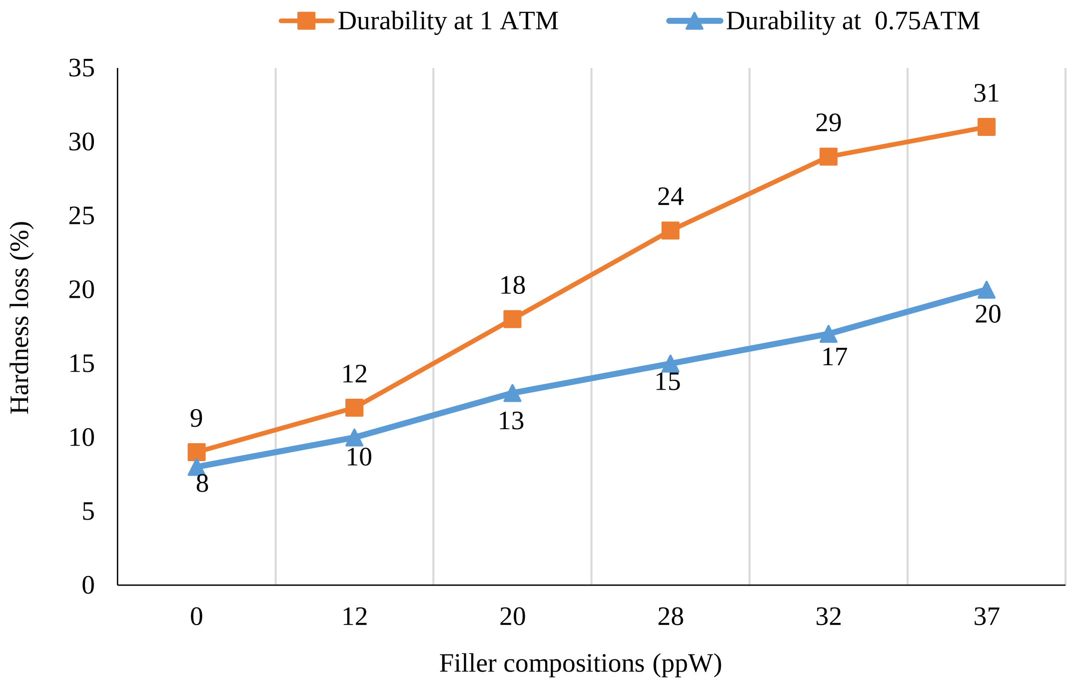


Figure 5. Effects of different atmospheric pressures (1atm & 0.75atm) and compositions of filler on the durability of flexible polyurethane foam
Note: *Sourced from self authored in Sheela foam Ltd. R&D Lab.*

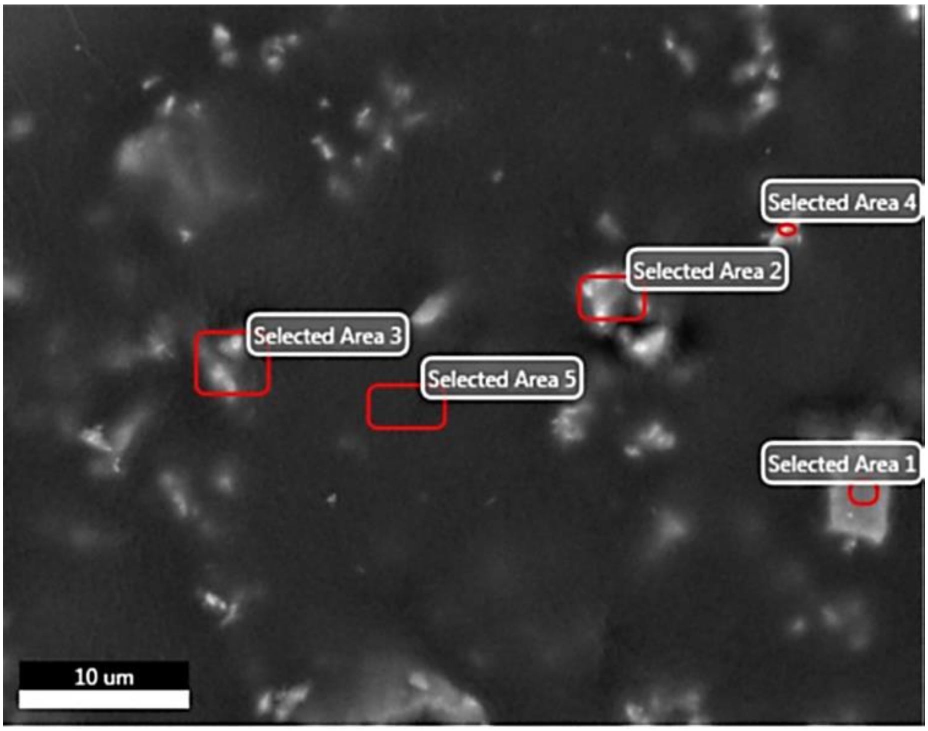


Figure 6. Qualitative spot mode of EDS analysis of Polyurethane foam produced at 1 atm.
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

Elements and weight percentage distribution were observed in the EDS Analysis. It was found that the uniform filler dispersion was present at both vacuum and ambient pressure conditions. At 1atm, Fillers contain Fe oxide, $CaCO_3$ and alumina silicate material (Table 5) and at 0.75 atm, Fillers contain $CaCO_3$ and oxides of Mg, Si and Fe (Table 6).

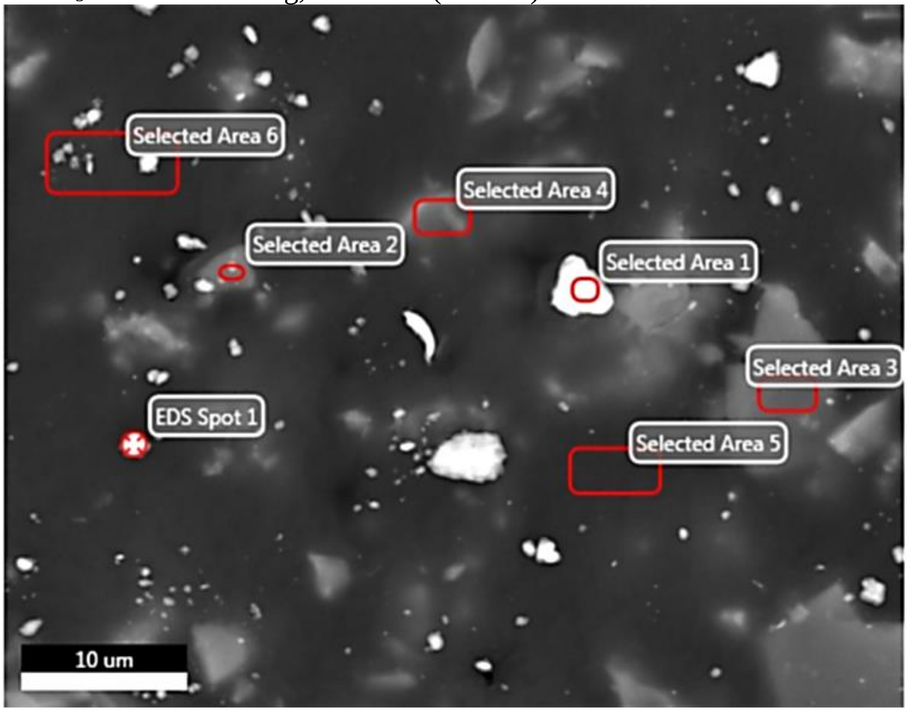


Figure 7. Qualitative spot mode of EDS analysis of Polyurethane foam produced at 0.75 atm.
Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

Table 5. Elements and weight percentage distribution [At 1atm].

Elements	**Weight %**				
	Area 1	***Area 2***	***Area 3***	***Area 4***	***Area 5***
O K	43.71	29.15	32.69	24.81	22.41
Si K	-	2.19	-	6.68	-
Ca K	22.16	6.60	14.18	4.81	2.77
Fe K		-	-	-	-
Mg K	15.35	4.39	6.88	2.97	1.08
N K	-	5.19	2.57	3.84	5.47
C K	18.78	49.69	43.68	49.51	68.29
Na K	-	1.37	-	2.54	-
Al K	-	1.13	-	4.07	-
Cl K	-	0.29	-	0.62	-
K K	-	-	-	0.15	-

Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

Table 6. Elements and weight percentage distribution [At 0.75atm].

Elements	**Weight %**						
	Spot 1	***Area 1***	***Area 2***	***Area 3***	***Area 4***	***Area 5***	***Area 6***
O K	34.73	17.06	35.68	38.37	32.72	18.79	23.37
Si K	0.81	0.54	0.27	-	-	0.02	0.19
Ca K	0.84	4.20	15.52	21.97	30.23	21.23	10.61
Fe K	30.53	49.16	1.87	-	-	-	6.41
Mg K	-	4.37	8.36	11.94	1.27	0.70	2.15
N K	-	-	3.51	3.43	5.31	1.45	0.65
C K	33.09	24.68	34.79	24.29	30.46	57.80	56.53

Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

SEM Analysis

To facilitate testing and analysis, each foam sample was meticulously cut into small, uniform pieces measuring (0.5 x 0.5 x 0.5 cm) using scissors. This standardized size ensured consistency in the dimensions of the samples and allowed for precise and comparable measurements across various mechanical properties. The fragmentation process was conducted with the aim of preparing representative specimens that could be effectively utilized for the detailed evaluation of the foam's performance in specified testing procedures. Subsequently, these foam samples underwent a gold-coating process. During microscopic analysis, it was observed that the cell size of the foam produced under vacuum conditions was larger, ranging from 130µm to 1.44mm, in comparison to the cell size of foam produced under ambient conditions, which ranged from 304µm to 946µm.

The flexible polyurethane foam samples were thoroughly examined under magnifications of 30x, 50x, and 100x, as illustrated in Figures 8 to 13. These microscopic analyses provided a detailed view of the foam's cellular structure at different levels of magnification, allowing for a comprehensive understanding of the impact of atmospheric conditions on the foam's microstructure.

Cell Morphology Results

The results of cell morphology, as depicted in Scanning Electron Micro-photographs (Figures 8-13), reveal the impact of varying pressure on the cell structure of flexible polyurethane foam. The main effect observed was the influence on cell growth, leading to distinct differences in the size and shape of the cellular structure.

Under atmospheric pressure conditions (1atm), the foam exhibited more regular and uniform cells, as seen in the SEM micro-photographs. In contrast, when the pressure was reduced to below atmospheric conditions at 0.75atm, the cell size became larger, and the cellular structure displayed non-uniformity and unevenness. The images in the provided figures illustrate the significant differences in cell size and morphology between foams produced under these two pressure conditions.

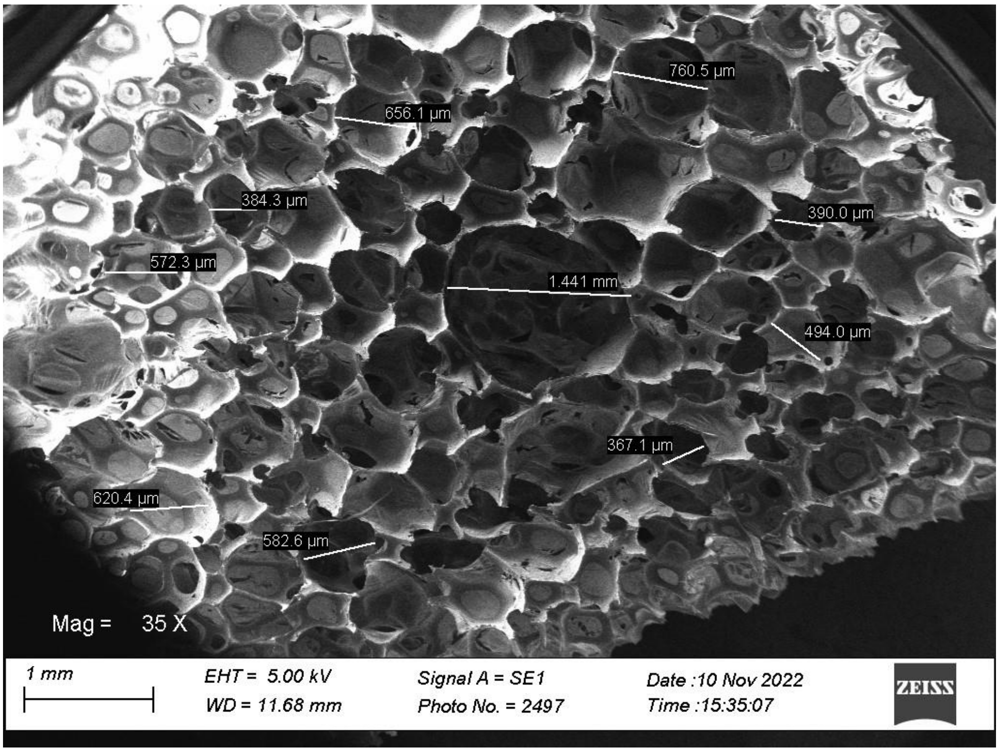


Figure 8. SEM of flexible polyurethane foam filled with calcium carbonate produced [At 1atm] (magnification of 30x) [Cell size- 495µm - 946µm]
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

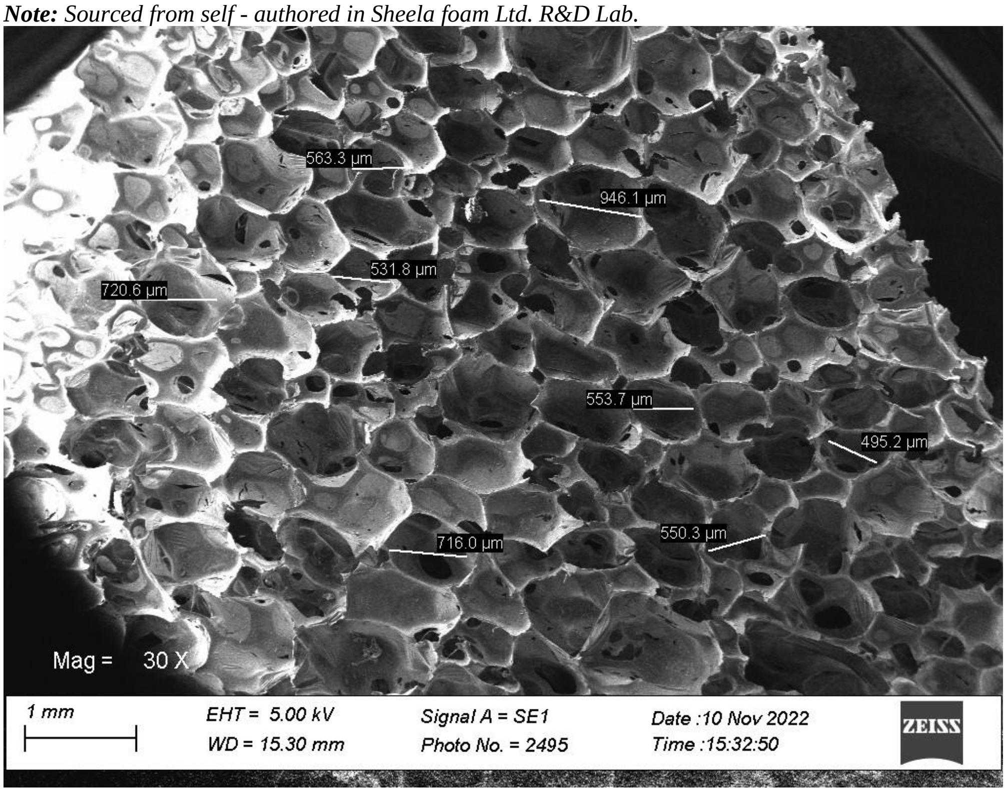


Figure 9. SEM of flexible polyurethane foam filled with calcium carbonate produced at below atmospheric pressure conditions (magnification of 35x) [Cell size- 390µm- 1.44mm].
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

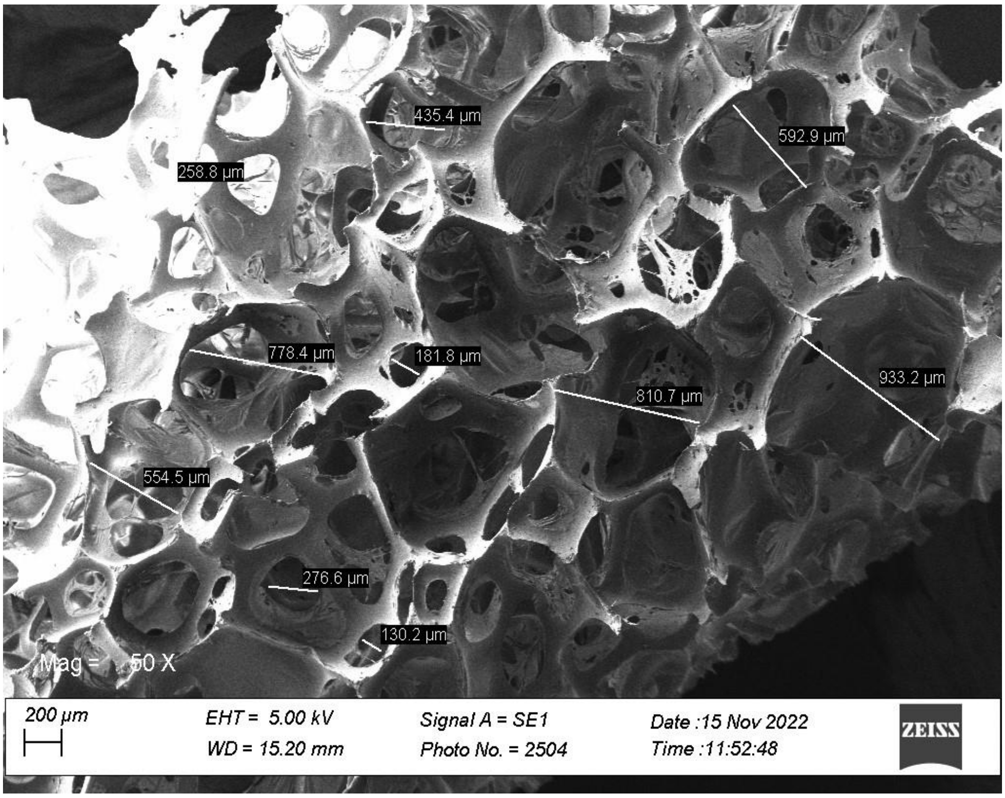


Figure 10. SEM of flexible polyurethane foam filled with calcium carbonate produced [At 1atm] (magnification of 50x) [Cell size- 304µm-799µm].
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

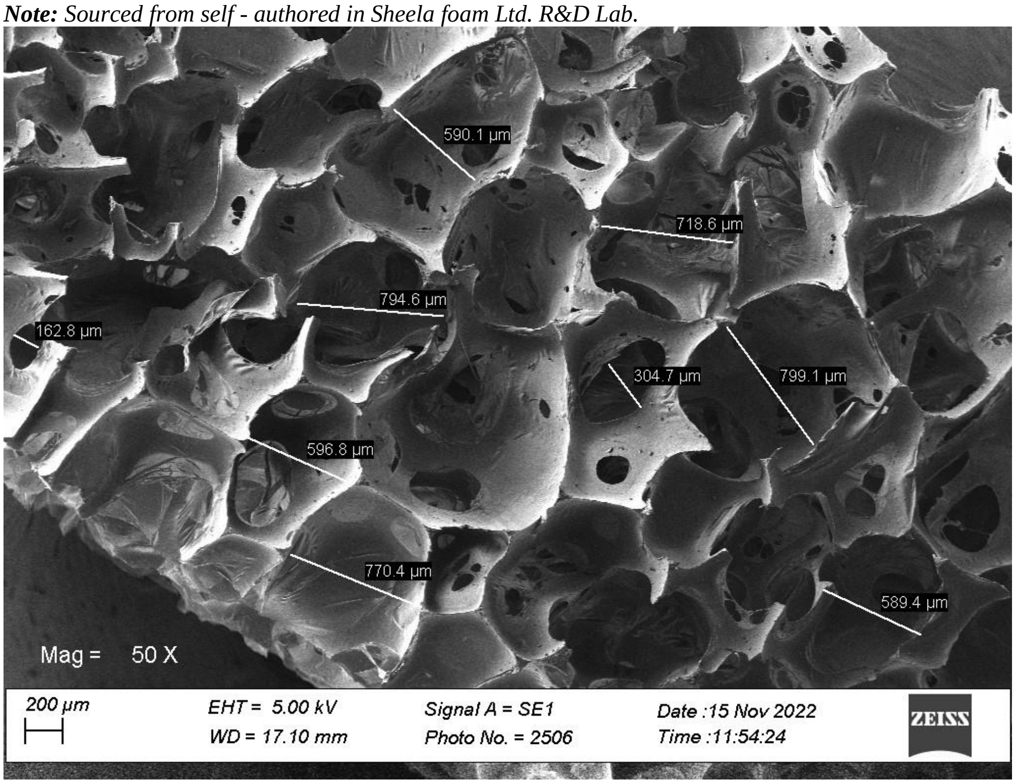


Figure 11. SEM of flexible polyurethane foam filled with calcium carbonate produced [At 0.75atm] (magnification of 50x) [Cell size- 130µm- 933µm].
Note: *Sourced from self - authored in Sheela foam Ltd. R&D Lab.*

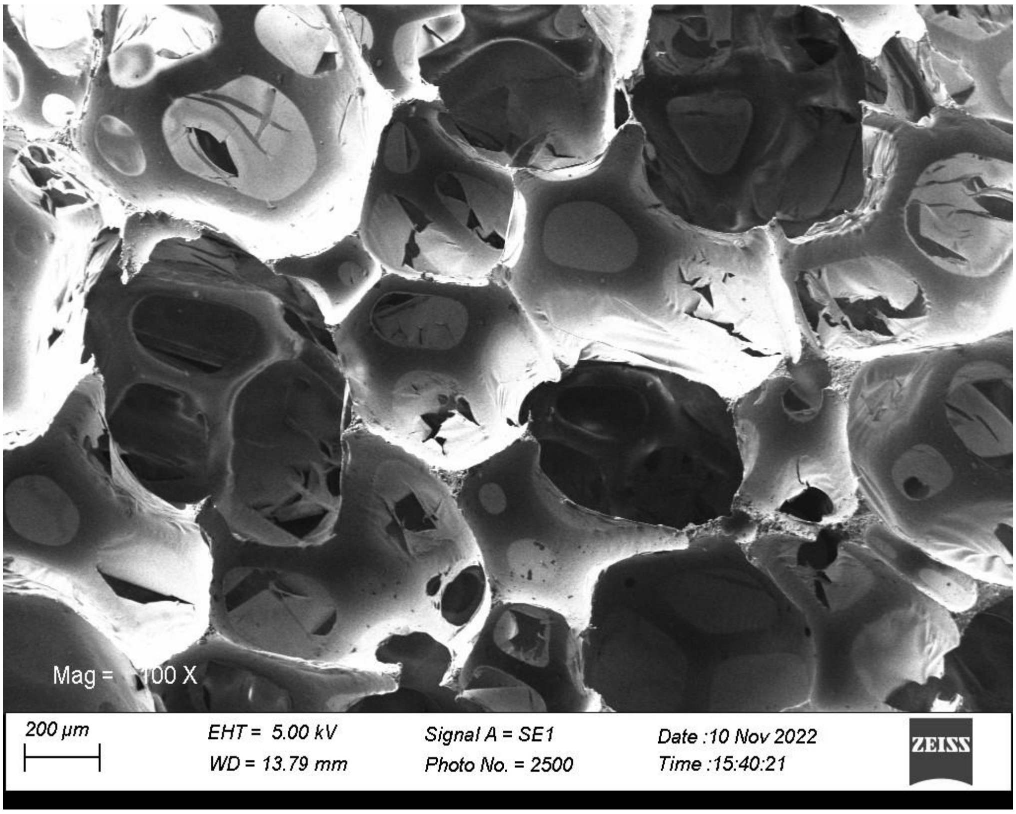


Figure 12. SEM of flexible polyurethane foam filled with calcium carbonate produced [At 1atm] (magnification of 100x) [Cell size- 390µm- 860µm].
Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

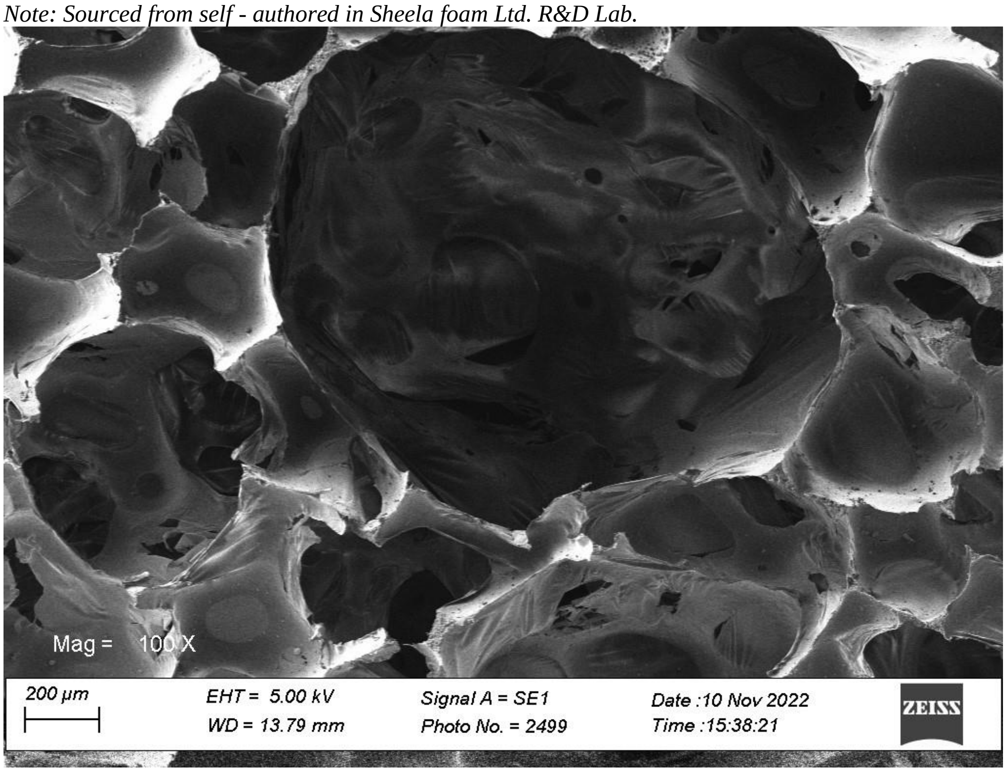


Figure 13. SEM of flexible polyurethane foam filled with calcium carbonate produced [At 0.75atm] (magnification of 100x) [Cell size- 390µm- 1.6mm].
Note: Sourced from self - authored in Sheela foam Ltd. R&D Lab.

CONCLUSIONS

The study revealed that the lack of symmetry in cell structures in the foam resulted in improved mechanical properties, particularly enhanced elongation and durability when compared to foams produced under normal atmospheric conditions (1atm). The uniform distribution of calcium carbonate filler played a significant role in achieving these improvements in the production of flexible polyurethane foam under below atmospheric pressure (0.75atm).

Foam produced under below atmospheric pressure conditions (0.75atm) demonstrated superior physical properties, including a bouncy feel, increased resilience, improved elongation, enhanced hardness, and reduced thickness loss percentage compared to foam produced under ambient pressure (1atm). There is a notable enhancement in the mechanical attributes such as compression set properties and durability. Hysteresis loss also showed significant enhancements when the foam was produced under below atmospheric pressure conditions, especially with an increased concentration of $CaCO_3$, in contrast to foams produced under standard atmospheric conditions (1atm).

The focus of this research paper is primarily on enhancing the mechanical properties and durability of filled polyurethane foam, with a specific concentration of 40 parts per hundred parts of polyol (ppw) of $CaCO_3$. This improvement holds particular significance in applications related to furniture, cushioning, and bedding, providing a distinct advantage in these contexts.

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