Applied Chemical Engineering (2025) Volume 8 Issue 1 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v8i1.5589

ORIGINAL RESEARCH ARTICLE

Study of the relationships between structural and mechanical properties of porous polymeric materials

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ABSTRACT

The materials of this article are dedicated to studying the relationships between the structural and mechanical properties of porous polymeric materials for their control. The research revealed that as the pore diameter of the polymeric material decreases, the Young's modulus decreases, while the yield strength increases. With an increase in the thickness of cell walls, the Young's modulus decreases, and the yield strength increases. A higher Young's modulus was found in samples with lower density, while the highest yield strength was observed in samples with the highest density.

Keywords: porous material; structure, mechanical properties; comparative studies

ARTICLE INFO

Received: 26 December 2024
Accepted: 8 February 2024
Available online: 14 February 2025

1. Introduction

Currently, foam materials are becoming increasingly popular and play a significant role in the modern world. They have gained particular importance in applications such as thermal and vibration insulation, sound absorption, liquid filtration, energy management, and others. Solid porous materials consist of two phases: a continuous rigid phase that forms the main porous structure and a blocking phase that creates pores in the solid material. In the presence of a gas medium in the pores, the blocking phase may consist of gas or, in the presence of a liquid medium in the pores, of liquid[1-6].

The production of porous materials with relatively low density and closed pores gives them unique mechanical properties, making high strength the main characteristic of porous materials. These exceptional properties make porous materials suitable for many applications that require lightness and high strength[7].

Materials with low stiffness and open pores, such as porous materials, are ideal for mechanical damping. Flexible porous materials are widely used in creating various devices due to their high compression resistance, making them ideal for energy absorption and material protection[8].

The influence of internal pore distribution on the elastic properties of closed-cell porous aluminum foam compared to the porosity of a cow femur bone. Two types of closed-cell porous foam were used in the study: with homogeneous and heterogeneous pore distributions. After conducting compression tests, the results were compared with the properties of a cow femur bone, followed by finite element method modeling. Analyzing the obtained results, the researchers suggested developing aluminum foam with closed pores technology, creating differences in their density. Additionally, the analysis showed that differences and gradual changes in pores did not significantly affect the micromechanical properties, while relative density turned out to be the main factor influencing the properties. The model created and calculated using the finite element method successfully predicted the material behavior, leading the researchers to suggest its use in future studies for the development of new porous materials[9].

The influence of changes in cell size and wall thickness on the strength of closed-cell porous materials, as well as studying the effect of differences in cell size and wall thickness on compression and shear applied to the samples using the Lagerra model. During the research, it was found that when changing the cell size and wall thickness, the compression and shear forces decreased, with compression force being more sensitive to these changes. The influence of differences in wall thickness on compression and shear forces was found to be similar to the influence of cell size[10].

The study focused on examining the influence of pore shape (elliptical and spherical) on the mechanical properties of porous metals. It was found that models with elliptical pores exhibit poorer mechanical properties compared to those containing spherical pores[11].

Additionally, it has been shown that various factors, such as pore shape, size, wall thickness, and relative density, differentially affect mechanical properties. Some researchers have identified relative density as the primary factor influencing mechanical properties, noting that higher material density results in a lower Young's modulus. Conversely, other studies have indicated that as cell size changes, Young's modulus gradually decreases, even when relative density remains constant[12].Porous polymeric materials consist of open and closed cells, where the open cells contain gas and solid pores interconnected evenly **Figure 1a** . The ability of liquids to penetrate through the porous body depends on the characteristics of the open and closed cells[13].

As for the closed cells in porous polymeric materials, they contain separate pores and distribution continues continuously in the polymeric phase. The gas phase occurs inside the isolated pores **Figure 1b**. Both types of pore structures occur simultaneously in real porous polymeric materials[13].

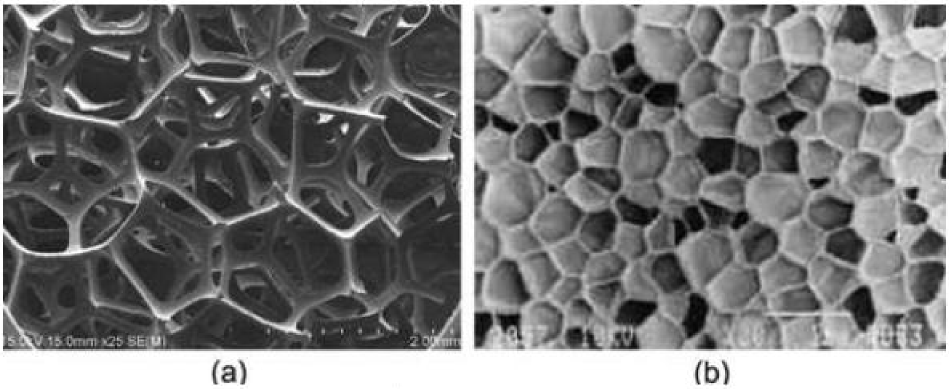

Figure 1. Three-dimensional porous polymeric foam: (a) open-cell polyurethane foam, (b) closed-cell polyvinyl foam.

The aim of the study is to investigate the influence of changes in the parameters of the structure of the studied porous polymer material (pore sizes, wall thickness, and density) by simulating the porosity of its structure on mechanical properties.

2. Materials and methods

The study was conducted using polyethylene material PE100, which was chosen due to its wide application and the presence of porous materials in it, as well as its availability on the market.

2.1. Sample preparation

A large block of this material was cut into small rectangular parallelepipeds with dimensions of 17.5x13x8 mm so that their shape corresponded to the experiments conducted on them. Then, to simulate porosity, the samples were drilled using drills used in dentistry with different diameters: 0.5 mm (minimum drill diameter), as well as 0.8, 1, and 1.2 mm. The holes on the samples were distributed so that each contained six holes, and increasing their diameters led to a decrease in the density and thickness of the cell walls. To verify the results, five sets were made (three samples in each), four of which differed in the diameters of the holes, and one consisted of samples without holes. Samples with and without holes are shown in **Figure 2**.

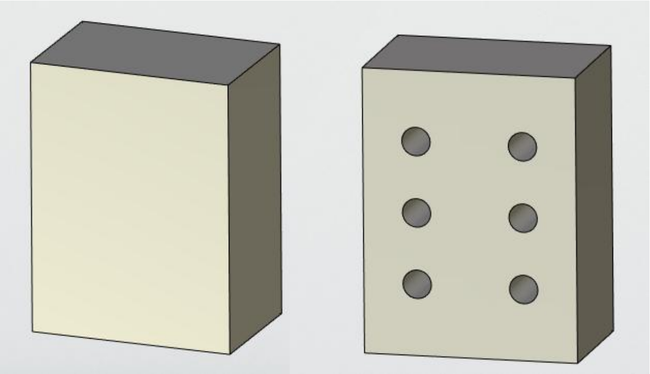

Figure 2. Samples with holes of different diameters and without holes.

These samples were created to be suitable for testing and simulating the structure of a porous material with closed and open pores. It is assumed that the open pore represents a cylinder, the lateral surface of which corresponds to the outer surface of a group of closely touching spheres (see **Figure 3**).

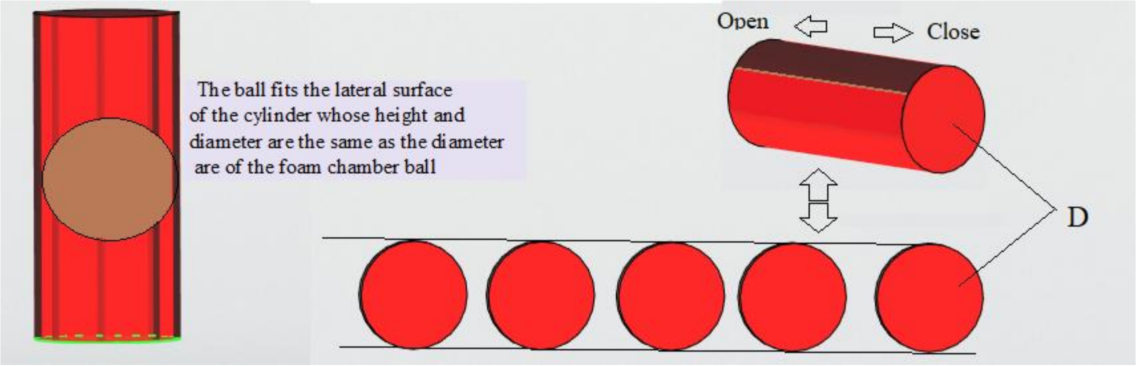

Figure 3. Porous material.

2.2. Test methodology

Compression testing, conducted on samples using a special setup, was interrupted at the onset of material deformation. Subsequently, the Young's modulus and elastic limit were determined (**Figure 4**), The numerical stress results were then analyzed using the SolidWorks program, developed by SolidWorks Corporation (USA). This computer-aided design (CAD) software offers a user-friendly virtual environment for modeling linear static motion over time and for analyzing high-cycle fatigue.

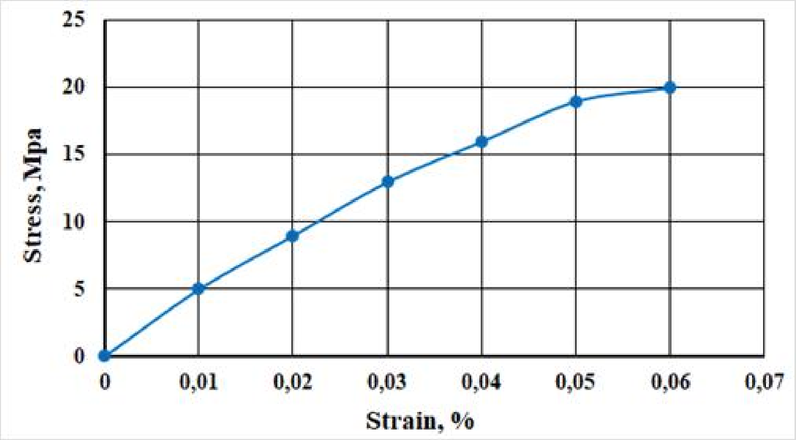

Figure 4. The stress-strain curve of one of the samples during compression testing was interrupted at the onset of elastic deformation.

3. Results and discussion

3.1. Experimental Results:

To determine the yield strength and Young's modulus at various parameters of the porous material, all prepared samples were subjected to compression testing (**Figure 5**), which included:

The results of the study on determining the changes in yield strength and Young's modulus depending on the pore diameter, wall thickness (nerve) and density: are shown in **Table 1.**

Table 1. Changes in yield strength and Young's modulus depending on Pore diameter,Wall thickness (nerve) and density.

Pore diameter, mm	Wall thickness, mm	Density ρ, Kg/m^3	Yield strength, Gpa	Young's modulus, Mpa
0.5	4	0.945	18	0.87
0.8	3.4	0.932	16.6	0.92
1	3	0.925	15	0.96
1.2	2.6	0.917	14.9	1

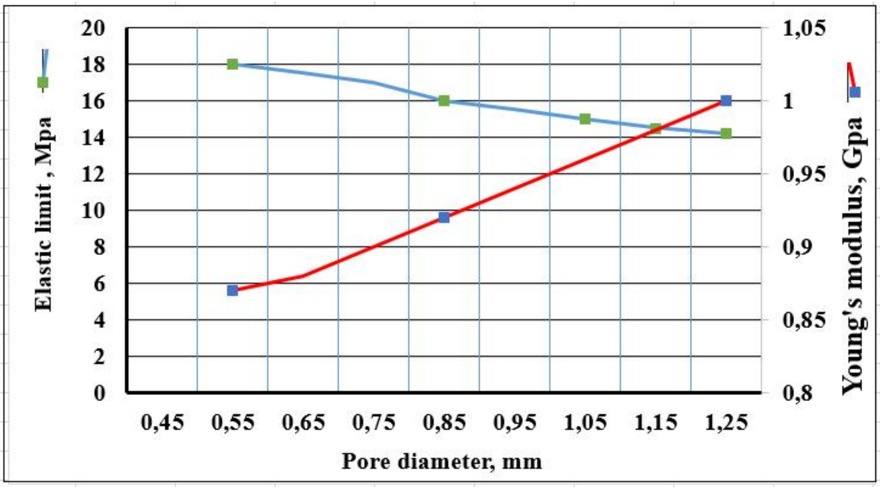

Figure 5. Results of changes in yield strength and Young's modulus depending on pore diameter.

From **Figure 5** and the data in **Table 1**, it can be seen that the highest value of Young's modulus was achieved when testing a sample with pores of diameter 1.2 mm, equal to 1 GPa. As the pore diameter decreased, Young's modulus began to decrease, reaching a value of 0.87 GPa for the sample with pores of diameter 0.5 mm. This is explained by the fact that increasing the pore diameter leads to a reduction in wall thickness and density, which increases the elasticity of the material. It was also noted that the highest value of yield strength was achieved in the sample with pores of diameter 0.5 mm - 18 MPa, and it began to decrease with increasing diameter, reaching a value of 14.19 MPa in the sample with pores of diameter 1.2 mm.

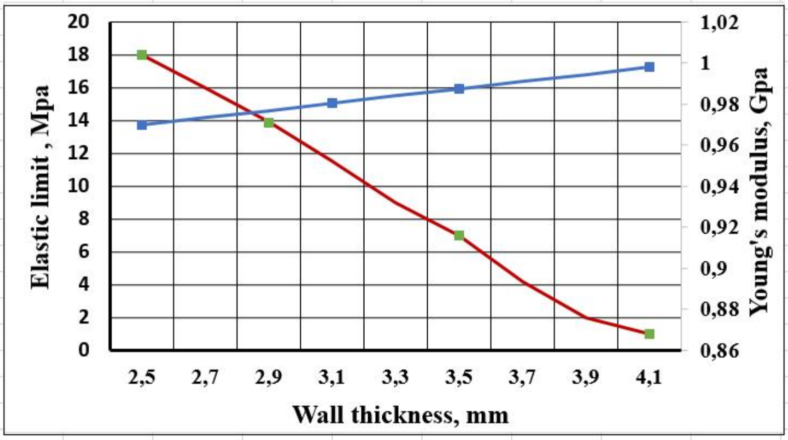

Figure 6. Dependence of the yield strength and Young's modulus on the wall thickness (nerve).

From **Table 1** and **Figure 6**, it can be seen that the highest value of Young's modulus, equal to 1 GPa, was observed in the sample with a pore diameter of 1.2 mm, corresponding to a minimum wall thickness of 2.6 mm, and then started to decrease to a minimum value of 0.87 GPa in the sample with a pore diameter of 0.5 mm and a maximum wall thickness of 4 mm. It is also noted that the highest value of yield strength was achieved with a maximum wall thickness of 4 mm, corresponding to a pore diameter of 0.5 mm, and then started to decrease as the wall thickness of the cell decreased, reaching a minimum value in the sample with a wall thickness of 2.6 mm and a pore diameter of 1.2 mm. Comparing these results with previous studies conducted by Redenbach and others, it was found that there is a similarity in that as the differences in cell (pore) sizes increase, Young's modulus gradually decreases while maintaining constant relative density.

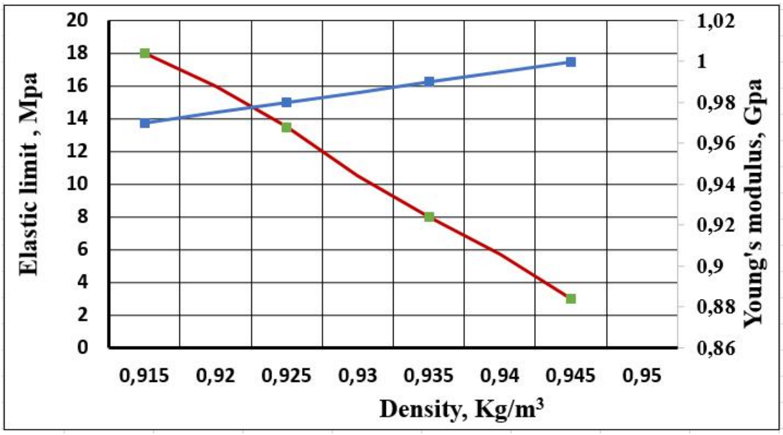

Figure 7. Relationship between yield strength, Young's modulus, and density Density, Kg/m^3.

From **Table 1** and **Figure 7**, it can be seen that the highest value of yield strength, equal to 18 MPa, is observed in the sample with a pore diameter of 0.5 mm and a density of 0.945, after which it starts to decrease, reaching a minimum value of 14.19 MPa in the sample with a pore diameter of 1.2 mm and a density of 0.917. These results are consistent with the study conducted by Hani E. and his colleagues[14].

3.2. Finite element analysis study

For this study, computer models of samples with hole diameters ranging from 0.5 mm (the smallest hole diameter) to 1.2 mm were created using Solidworks software. These models were subjected to compressive loads according to the experimental research data. As a result, the following data were obtained:

Sample with 0.5 mm diameter holes: **Figure 8** shows the region of the sample around the hole under load and the stress distribution on it.

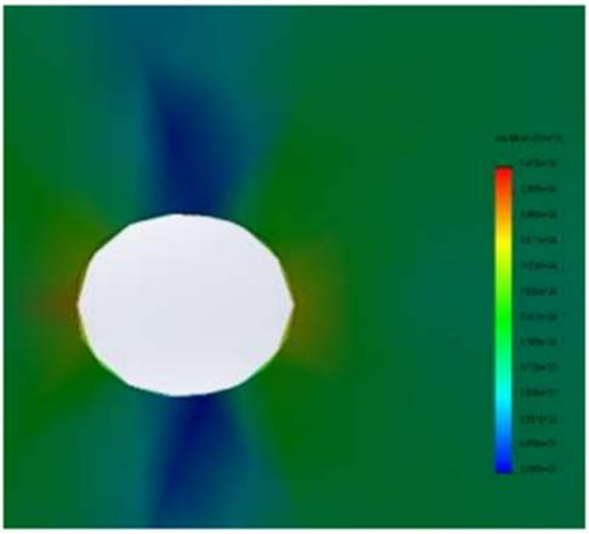

Figure 8. Stress distribution in the area of the sample around the 0.5 mm diameter hole under load.

Sample with 1.2 mm diameter holes: **Figure 9** shows the area of the sample around the hole under load and the stress distribution on it.

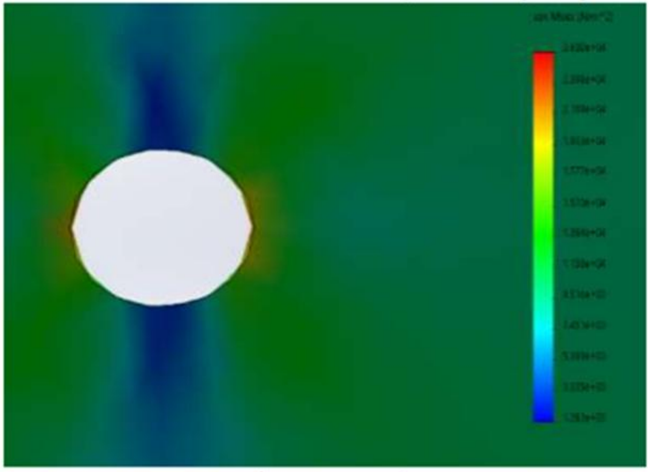

Figure 9. Stress distribution in the area of the sample around a hole with a diameter of 1.2 mm under load.

The analysis of **Figures 8** and **9** reveals that the yield stress increases as the diameter of the hole expands. This is attributed to the numerical study's consideration of area reduction and shear displacement surrounding the hole. Consequently, the impact of the hole's presence on the material's stress distribution is accurately assessed. Upon comparing the results from experimental tests on samples with holes to the calculated methods, it becomes clear that there are notable discrepancies between them. This divergence can be attributed to the experimental approach, which did not factor in the shear displacement path around the hole. As a result, stress values within the hole diminished with increasing diameter. In contrast, the calculations included this displacement, underscoring the significance of considering various factors in both experimental and computational analyses to gain a thorough understanding of material behavior.

4. Conclusions

The study has shown that parameters of porous polymer materials, such as pore diameter, wall thickness, and density, significantly influence their mechanical properties. As the pore diameter decreases, the Young's modulus decreases, which may be attributed to changes in the material's microstructure. Simultaneously, the yield strength increases, indicating an improvement in material strength with a higher number of pores.

Changes in wall thickness also affect the mechanical characteristics of the material: an increase in wall thickness leads to a decrease in Young's modulus but an increase in yield strength. This can be explained by changes in stress distribution within the material.

Regarding material density, the results showed that Young's modulus is higher in materials with lower density, which may be due to an increase in voids within the material. However, the yield strength reaches its highest values in materials with the highest density, indicating a more compact and strong structure.

Thus, these findings emphasize the importance of controlling the parameters of porous polymer materials to achieve optimal mechanical properties and provide a better understanding of the influence of microstructure on overall material strength. Further research in this field can aid in the development of new materials with improved characteristics for various applications.

This study highlights the importance of using both experimental and computational methods to comprehensively understand material behavior. Researchers should pay attention to how various factors, such as holes and displacements, affect the results, allowing them to improve their designs and predictions.

Conflict of interest

The authors declare no conflict of interest.

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