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Professional paper

INFLUENCE OF PROCESS PARAMETERS ON THE PHYSICAL AND MECHANICAL PROPERTIES OF EXTRUDED POLYSTYRENE

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ABSTRACT

In this work, I aim to examine the various influences of process parameters on the physical and mechanical properties of extruded polystyrene. Since XPS belongs to the group of thermoplastic polymers, its properties are significantly affected by thermal treatment, particularly temperature and pressure. However, in addition to these key factors, this paper also aims to examine the impact of other parameters. Production, sampling, parameter monitoring, and sample testing were conducted in the production facility and the laboratory for construction materials within the TEMAX BH d.o.o. company. The findings of this research are expected to provide valuable insights into optimizing manufacturing conditions to enhance XPS performance, thereby improving material efficiency and expanding its potential applications in the construction and insulation industries.

Keywords: XPS, process parameters, extruded polystyrene, compressive strength, and melt flow index.

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1. INTRODUCTION

XPS, also known as extruded polystyrene, is a thermal insulation material widely used in building construction and beyond.

The production process of XPS rigid foam involves the following steps:

1. Thermoplasticization of solid polymer and additives;
2. Injection of a physical foaming agent and initial mixing;
3. Cooling the resulting mixture to optimal foaming temperatures, ensuring complete dissolution of the foaming agent;
4. Foam stabilization, shaping, and finishing to final dimensions [1].

Solid XPS foam is produced through a continuous extrusion process in which solid polystyrene granules are melted with various additives to enhance the process and production efficiency. The most common additives include foaming agents, lubricants, antioxidants, plasticizers, blowing agents, colorants, and flame retardants, among others. Each additive has a recommended usage and dosage. For example, when selecting a flame retardant, an increase in thermal stability typically results in a decrease in its reactivity or activity [2-4].

Blowing agents, which are gases used to create a cellular structure within the foam, play a key role in determining the material's thermal properties. Using gases with low

thermal conductivity improves thermal insulation performance. "Hydro nuc" (H.N) is a chemical nucleating agent that releases CO_2, ensuring a very fine, dense foam structure with a high nucleation degree [5,6]. The XPS production process begins with the introduction of polystyrene raw material and auxiliary components in a specific ratio via an automated dosing system. The polystyrene granules are fed into the primary extruder under controlled temperature and pressure conditions, where they are heated and melted along with additives into a viscous fluid. This molten mixture is then filtered and transferred to the secondary extruder, where it undergoes further melting and compaction. Using controlled heating and pressure, the molten mass is extruded through a wide-slot nozzle to form the foam. The flow of XPS foam is regulated by the screws of the extruder head. After passing through the calibrator, the foam mixture is considered a semi-finished product and is transported in a continuous strip to a machine for surface treatment and cutting. During transportation, the semi-finished product cools rapidly, which may cause slight variations in thickness and width, though these are generally negligible. The production line can also include additional surface treatments, such as creating a waffle texture or cutting channels into the surface. Finally, the product is cut to the desired board length [7-10]

2. EXPERIMENTAL

The experimental phase begins with the establishment and monitoring of process parameters, which are defined based on several factors. One of the key factors is the polymer granulate itself, particularly its technical characteristics and processing requirements, including its rheological properties, such as the melt flow index (MFI). Once sampling is completed, the XPS panel is taken to the laboratory, where it is measured, weighed, and prepared to the appropriate dimensions. According to BAS EN 826:2014, "Thermal Insulating Products for Building Applications – Determination of Compression Behavior," the test specimens must be precisely cut into square shapes with the specified dimensions:

1. 50 mm × 50 mm or
2. 100 mm × 100 mm or
3. 150 mm × 150 mm or
4. 200 mm × 200 mm or
5. 300 mm × 300 mm [11].

Compressive strength was tested at a deformation of 10%. The compressive stress at 10% strain, σ_{10}, in kPa, is calculated according to Eq. (1):

$$\sigma_{10} = 10^3 \frac{F_{10}}{A_o} \quad (1)$$

where F_{10} is the force corresponding to a strain of 10 %, in newtons, and A_0 is the initial cross-sectional area of the specimen, in square millimeters.

For this test, the machine model TC050369, manufacturer LABOMAK, was used.

According to the standard BS EN 1604:2013 "Thermal insulating products for building applications - Determination of dimensional stability under specified temperature and humidity conditions" to calculate the dimensional changes, $\Delta\varepsilon_l$, $\Delta\varepsilon_b$, and $\Delta\varepsilon_d$, in percentage, from the individual measurements, using Eq. (2), Eq. (3) and Eq.(4):

$$\Delta\varepsilon_l = 100 \frac{l_t - l_0}{l_0} \quad (2)$$

$$\Delta\varepsilon_b = 100 \frac{b_t - b_0}{b_0} \quad (3)$$

$$\Delta\varepsilon_d = 100 \frac{d_t - d_0}{d_0} \quad (4)$$

where l_0, b_0, and d_0 are initial dimensions after conditioning, in mm, and l_t, b_t, and d_t are final dimensions, after exposure to temperature, in mm [12].

For the purpose of this test, the machine model BKHS120-2103004, manufacturer BLULAB, was used.

According to the standard BAS EN 12087:2014 "Thermal insulating products for building applications - Determination of long-term water absorption by immersion" test specimens need to be squares with squarely cut edges having sides of (200 ± 1) mm to calculate the water absorption after

the immersion time of 28 days, W28, in percent volume using formula (5):

$$W_{28} = 100\frac{m_{28}+V_1*\rho_w-m_0-m_1}{V_0*\rho_w} \quad (5)$$

where m_0 is the initial mass of the test specimen, in kilograms, m_1 is the mass of the empty cage immersed, in kilograms, m_{28} is the mass of the test specimen and the cage submerged after 28 days of immersion, in kilograms, $V_0 = l_0 \times b_0 \times d_0$ is the initial volume of the test specimen, in cubic meters, $V_1 = l_1 \times b_1 \times d_1$ is the volume of the test specimen after 28 days of immersion, in cubic meters, ρ_W is the density of water, assumed to be 1000 kg/m^3, W_{28} shall be rounded to the nearest 0.1 volume percent, [13]. All testing was carried out at (23 ± 5) °C (50 ± 5) % relative humidity.

3. RESULTS AND DISCUSSION

Three different types of sample testing were performed: compressive strength, dimensional stability under specified temperature and humidity conditions, and long-term water absorption by immersion. This study compared the results in relation to the following influences of process parameters: different MFI, different proportions of additives, and different surface finishes.

3.1. Different MFIs

From each XPS board, 5 samples of 100 x 100 mm dimensions were created. The samples are sampled in such a way that the entire board is tested across the width. The samples differ only in the type of granulate, while the other additives and parameter settings are the same or relatively the same. Granulate with an MFI of 3.5 g/10 min is in sample number 2, while granulate with an MFI range of 2.5 to 3 g/10 min is in sample number 1. Figures 1 and 2 show the force-displacement curves for samples 1 and 2. For Samples 1 and 2, five replicate tests were performed. Five specimens were cut from a single large board of the same composition and material properties, ensuring consistency among the tested specimens. Each specimen was tested separately, and the results shown in Figure 1 correspond to these five measurements as well as figure 2.

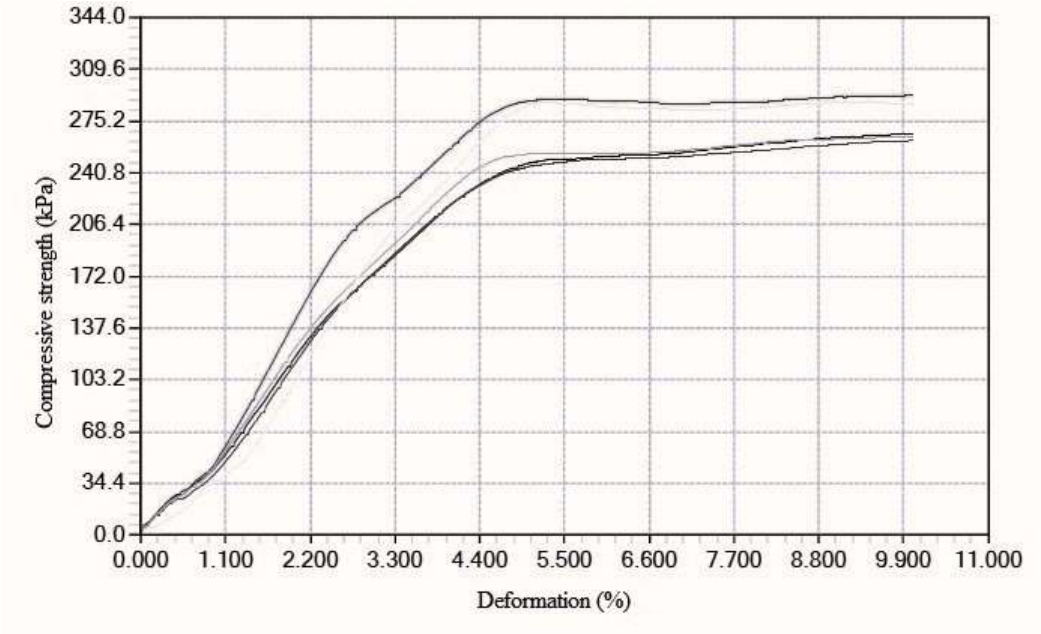

Figure 1. Compressive Strength–Defromation Diagram of sample 1.

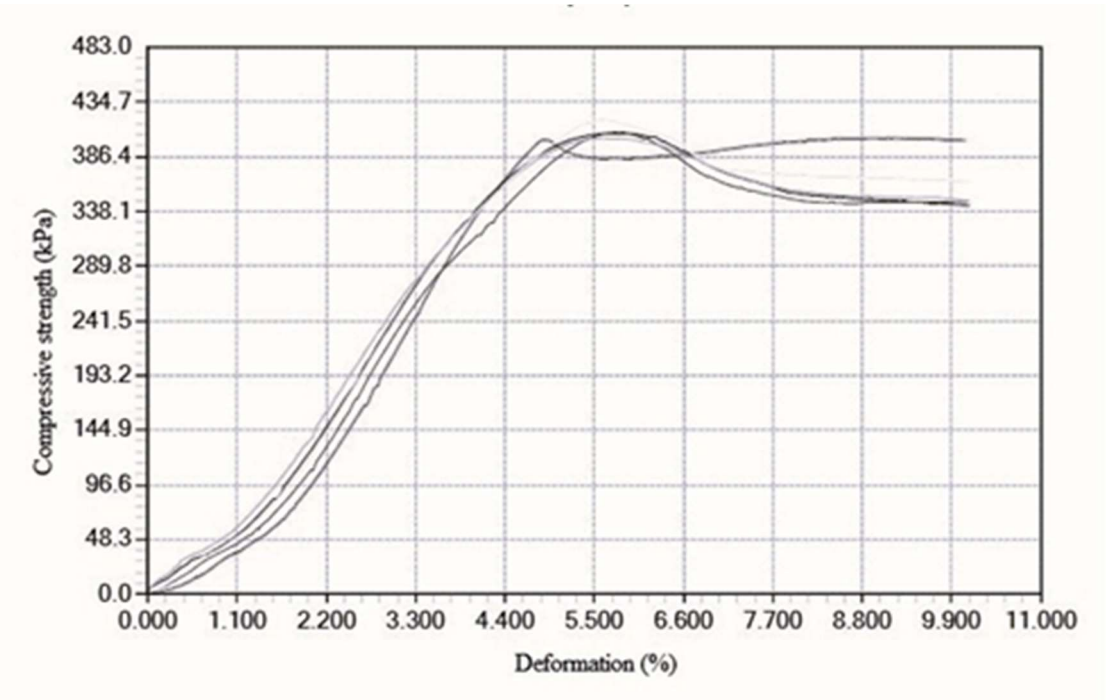

Figure 2. Compressive strength vs deformation of XPS sample of sample 2.

Table 1 shows the average values of mass, density, and compressive strength of the tested samples. All samples were tested on the day of their production.

Table 1. Average values of mass, density and compressive strength of samples 1 and 2

Sample	Mass (g)	Density (g/m^3)	Compressive strength (kPa)
1	14.98	30.32	274.8
2	16.19	32.87	407.9

By analyzing samples 1 and 2, we observe differences in all three parameters. The sample with a granulate whose MFI is 3.5 g/10 min shows higher compressive strength. Since a higher MFI means the material flows more easily when melted (lower viscosity) and a lower MFI means the material is more viscous and flows less easily, we can conclude that when the molten material flows more easily, better compressive strength results are obtained.

Also, better flow leads to a more homogeneous distribution of the polymer melt, resulting in a more uniform and dense cellular structure. This enhances compressive strength because the material is less prone to structural weaknesses. It should be noted that density itself is an indicator of compressive strength. Namely, the greater the mass of the sample and therefore the density, the compressive strength will always be higher than for samples with a lower mass. At the time of sampling, the difference in the material flow rate for samples 1 and 2 is insignificant and amounts to 6 kg/h or 1.3%. The observed differences in compressive strength confirm the critical role of MFI in the production of XPS insulation materials.

3.2. Different proportions of additives

The study further examined how varying the proportions of additives, particularly CO_2 and nucleating agent (H.N.), influences the physical properties of XPS panels. Table 2 shows the ratios of several raw materials, while Table 3 shows the average values of mass, density, and compressive strength of the tested samples.

All samples were tested on the day of their production. From each XPS board, 5 samples of 100 x 100 mm dimensions were created. The samples are sampled in such a way that the entire board is tested across the width.

Figures 3 and 4 show the force-displacement curves for samples 3 and 4.

For Samples 1 and 2, five replicate tests were performed. Five specimens were cut from a single large board of the same composition and material properties, ensuring consistency among the tested specimens. Each specimen was tested separately, and the results shown in Figures 1 and 2 correspond to these five measurements.

Table 2. Ratios of several raw materials

Sample	GPPS	H.N.	CO_2
3	91.04 %	0.16 %	1.36 %
4	90.98 %	0.12 %	1.12 %

Table 3. Average values of mass, density, and compressive strength of samples 3 and 4

Sample	Mass (g)	Density (g/m^3)	Compressive strength (kPa)
3	16.07	32.28	381.9
4	15.20	30.41	326.3

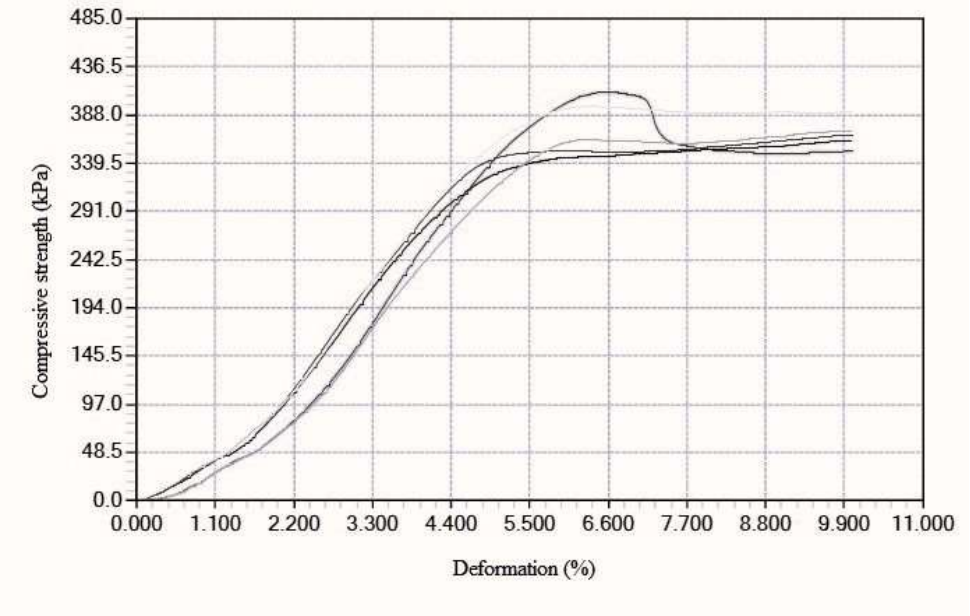

Figure 3. Compressive strength vs deformation of XPS sample 3

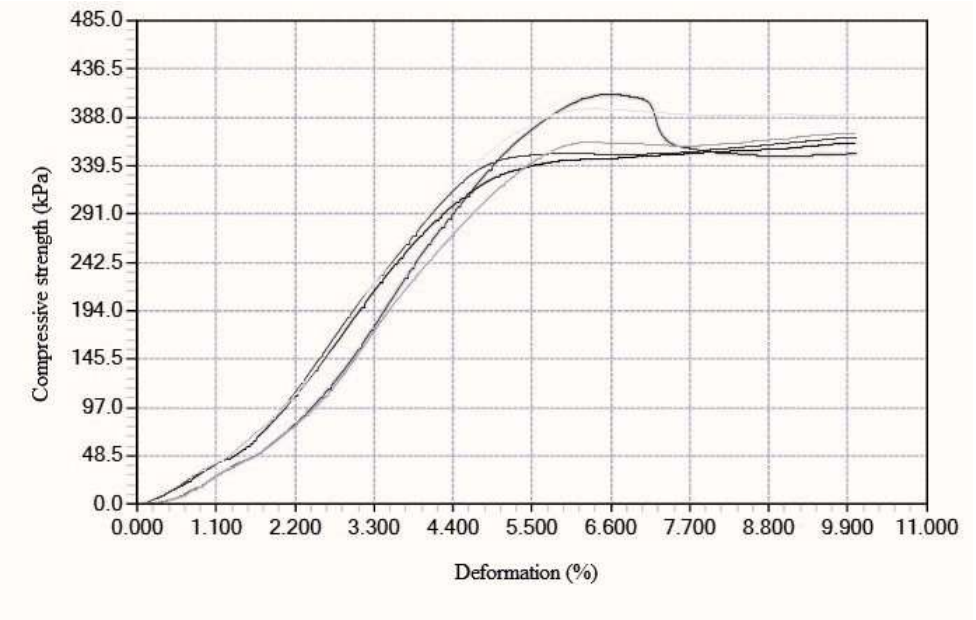

Figure 4. Compressive strength vs deformation of XPS sample 4

Analyzing the test results of samples 3 and 4, we see that by increasing the percentage of CO_2, as well as increasing H.N., the samples, and the extension XPS boards have better mechanical properties in the form of compressive strength.

These additives influence the cell structure of the foam, resulting in enhanced mechanical properties. However, careful optimization is required, as excessive additive concentrations may negatively impact other properties such as thermal insulation and long-term stability. The amount of CO_2 influences cell size and density. For example, too little CO_2 means fewer gas bubbles, denser foam, reduced insulation, but higher strength, and too much CO_2 means excessive expansion, larger cell size, and weaker structure.

The nucleating agent (H.N.) promotes smaller, more evenly distributed bubbles, leading to a denser foam with uniform cell structure, which improves compressive strength and a more stable material with lower risk of deformation over time.

The right balance of CO_2 and nucleating agents creates an optimal foam structure, increasing compressive strength without compromising insulation properties.

The proportion of GPPS in both samples is relatively the same as the specifications of the finished product and process parameters, except for the proportion of the additives already mentioned. Table 4 presents the relationship between additive proportions and compressive strength, demonstrating a direct correlation between increased CO_2 content and improved mechanical performance. From Table 4, we see that, in addition to the compressive strength, the mass and therefore the density of the sample with an increased proportion of the additives mentioned is greater. The total amount of input raw material for sample 4 is greater than sample 3 by 11.31 kg, which is approximately 1.18% of the total amount of input raw materials. Thus, sample 3 has a smaller amount of input raw materials at the time of sampling and a higher proportion of H.N. and CO_2.

3.3. Different surface finishes

After conditioning, three 200 x 200 mm samples are cut out from one XPS board. Table 4 shows the results of dimensional stability under specified temperature and humidity conditions, that is, the contraction

and expansion of samples. The results show the mean value of all three samples.
The samples were measured three times in length, three times in width, and five times in thickness. After that, the samples were placed in a drying oven at 60 °C for 48 hours. After conditioning, the samples were measured again at the same marked places. Using mathematical formulae (2), (3), and (4), the dimensional changes are calculated in percentage. Sample 5 has a surface with a waffle texture, while sample 6 has a surface with openings in channels. After conditioning, three 200 x 200 mm samples are cut out from one XPS board. Table 5 shows the results of long-term water absorption by immersion. The results show the mean value of all three samples. Sample 7 has a surface with a waffle texture, while sample 8 has a surface with openings in channels.

Table 4. Calculated dimensional changes of samples 5 and 6

Sample	$\Delta\varepsilon_l$	$\Delta\varepsilon_b$	$\Delta\varepsilon_d$
5	0.17 %	0.16 %	0.90 %
6	0.09 %	0.20 %	1.00 %

Table 5. Long-term water absorption by immersion of samples 7 and 8

Sample	W_{28}
7	1.37 %
8	1.09 %

4. CONCLUSION

The study confirms that process parameters play a crucial role in defining the physical and mechanical properties of XPS. The findings indicate that even minor variations in key parameters, such as the melt flow index (MFI), additive composition, and surface finish, can significantly affect the material's compressive strength, density, dimensional stability, and water absorption properties.
The key findings include:

1. MFI: Higher MFI results in improved compressive strength due to better material flow during processing;
2. Additive Proportions: Increased CO_2 and nucleating agent (H.N.) enhance the mechanical properties, including compressive strength and density;
3. Surface Finish: XPS panels with channel openings exhibit better dimensional stability and lower water absorption compared to waffle-textured surfaces.

To further refine the production and application of XPS, future studies should explore the long-term durability of different formulations under real-world conditions, including temperature fluctuations and prolonged exposure to moisture. Additionally, research into alternative foaming agents with lower environmental impact could help improve the sustainability of XPS production. Further investigations into the trade-offs between mechanical strength, thermal insulation, and process efficiency will be essential for optimizing the material for a broader range of applications in the construction and insulation industries.

Conflicts of Interest

The authors declare no conflict of interest.

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