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INFLUENCE OF PHYSICAL PROPERTIES ON THERMAL CONDUCTIVITY OF POLYSTYRENE INSULATION MATERIALS

Zahida Ademović[1,*], *Jasmin Suljagić*[1], *Jasmin Zulić*[1]
[1] University of Tuzla, Faculty of Technology,
Univerzitetska 8, 75000 Tuzla, Bosnia & Herzegovina

Abstract: Polymers based on polystyrene are widely used as thermoplastic materials due to the diversity in application, easy processability and a relatively low price. About 45% of the produced polystyrene is produced as compact and foamed products. Cellular foam polystyrene could be produced as expanded polystyrene (EPS) and extruded polystyrene (XPS) and is mainly used as insulation material. Therefore, physical and chemical properties of expanded and extruded polystyrene is of particular importance for thermal conductivity of the material. In this study, four types of expanded polystyrene were tested. Coefficient of thermal conductivity and the resistance of heat transfer were measured and compared to as well as mecahnical properties of the materials. It was confirmed that the density and thickness of the polystyrene influence the resistance of heat transfer.
Keywords: polystyrene, thermal conductivity, heat transfer.

1. INTRODUCTION

Due to the diversity in application, easy processability and a relatively low price, polymers on styrene basis have a high place in the overall global consumption of thermoplastics. Polystyrene (PS) is one of the most used polymer materials. It is thermoplastic linear macromolecule of general molecular formula $[-CH_2-CH-(C_6H_5)-]_n$ (Figure 1).

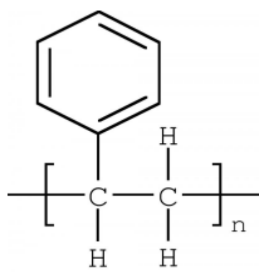

Figure 1. Chemical formula of polystirene

Styrene is one of the few monomers which polymerise by all chain polymerization mechanisms: free radical, cationic and anionic polymerization. Industrial polymerisation process take place only by the free-radical mechanism, initiated thermally or in the presence of initiator. The polymerization is carried out in mass or in suspension and rarely in the solution or emulsion. Such polymerization produces linear atactic polystyrene structure in which the phenyl groups (C_6H_5-), as substituents, are arranged randomly in macromolecule. Atactic polystyrene is amorphous, slightly tough, transparent, glass like material, has a high refractive index and has a high permeability for the visible part of the light.

PS has a relatively low glass transition temperature, 80 to 100 °C, the density of 1.05 to 1.07 gcm^{-3} and the average relative molecular weight of 60 000 to 180 000. Because of relatively low glass transition temperature of PS homopolymer, it can be used without any change in the structure only up to 70 °C [1,2]. At temperatures of 300 °C and higher, PS depolymerizes (decomposes). Modification of PS with rubber results in two-phase system with high impact toughness. This modified polymer is called high-impact polystyrene (HIPS). By addition of hydrocarbons with low boiling point, a foamed material expanded polystyrene (EPS) can be produced. This material has a very wide application [3,4].

Materials based on PS undergo thermal and photochemical degradation under the influence of sunlight due to the adsorption of ultraviolet radiation. Degradation is first observed by colour change to yellow and subsequent loss of mechanical properties. Addition of up to 0.5% antioxidants reduces the heat and photochemical degradation of PS significantly. Due to the non-polar character of molecules, PS is totally resistant to the influence of water and shows good electrical insulation properti-

* Corresponding authors: zahida.ademovic@untz.ba

es. PS is easily processed because its melt viscosity is low in a wide temperature range which enables very good fills of the molds. PS could be processed with all the known methods of thermoplastics processing, in particular by injection molding, extrusion into sheets and films and blowing in the objects of different shapes in the temperature range between 180 and 250 °C [5]. Extruded sheets of modified PS can be further easily processed into products by molding in vacuum. Such objects made of PS are subsequently processed mechanically, thermally or by gluing and can be produced in all colors.

PS has very good application characteristics. An important application of polystyrene is in the form of expanded and extruded foam known as trade name „Styrofoam“. PS is mostly used as construction material, as packaging for food, cosmetics, pharmaceutical and chemical products and as an insulator in the construction industry. Properties of PS are similar to those of structural polymeric materials, with very good electrical insulating properties and good heat stability (melting point around 240 ˚C). These properties allow PS to be used as blend with other polymers, in electrical engineering, electronics and as insulating materials in the construction industry [6-9]. However, the most widely used application of PS is as insulation material.

In the construction industry, for thermal insulation, two types of polystyrene are used: expanded polystyrene (EPS) and extruded polystyrene (XPS).

EPS as a product was patented by German concern BASF in 1954, which produced the material under the brand name Styropor. EPS is produced by mixing of PS with volatile liquids such as dichloromethane. By heating, volatile liquid expands and PS swells to the specified shape and weight. Due to the increased pressure in heated cylinder of extruders, the liquid does not evaporate. During the extrusion process, pressure drops sharply and the liquid evaporates rapidly increasing volume in the melt of polystyrene. In that way PS expands and at the same time is cooled. In the cooled material which is solid foam hollow cells remain. EPS is stiff and it is very tough foamed polymer materials. It has good characteristics, it is good thermal and acoustic insulator, absorbs little water and has a low water vapor permeability. These characteristics are preserved in a wide temperature range of -180 to +75 °C.

Extruded polystyrene (XPS) is produced by passing the pre-expanded mixture through an extruder during which the beads of polystyrene squeeze in a closed structure with a significantly greater mechanical strength and resistance to water absorption. It is used for thermal insulation of walls, floors and roofs. This material has a closed cells and practically does not absorb water. Despite the higher price compared to EPS, this product is used in places where the thermal insulation material is in direct contact with water. In contrast to the usual white EPS, XPS is colored (light blue, light green, pink) and the color is characteristic of each manufacturer.

Generally, the properties of polymeric materials are not constant but vary by changing the temperature, pressure and environment. Knowledge of the thermal properties can optimize the treatment process in order to improve product quality and save thermal energy. Also, thermal behavior of polymers in use can be improved. The most important thermal properties of polymers are:

- calorimetric properties such as thermal conductivity and the specific heat capacity,
- properties due to the volume changes such as the density or specific volume, linear coefficient of thermal expansion, coefficient of cubic expansion and compressibility,
- the time dependence of diffusion and penetration of heat such as thermal diffusivity and thermal penetration [10].

2. MATERIALS AND METODS

2.1. Materials

Following materials are used for the experimental analysis of physical, chemical and mechanical properties:

− Expanded polystyrene - EPS F
− Expanded polystyrene - EPS 120
− Expanded polystyrene - EPS 150
− Expanded polystyrene - EPS 200.

All analysis are performed in the Institute GIT d.o.o Tuzla, Bosnia and Herzegovina.

2.2. Methods

The test samples must be taken from the same sample with a total area of minimum 1 m^2. Conditioning of test samples must be done at least 6 hours at a temperature (23 ± 5) °C.

Length and width are tested in accordance with standard BAS EN 822 and thickness in accordance with the standard BAS EN 823. The measurements are carried out with caliper with accuracy of 1 mm after conditioning the samples, in several different places, min. 6 measuring points. The mean value of the measurement is a measure for assessing the conformity of products. The results must not deviate from the nominal value of the declared class. Testing of dimensions stability is done in constant normal laboratory conditions as well as in specific conditions of temperature and humidity. Normal laboratory conditions are temperature of 23 °C and relative humidity of 50%. Testing is performed in accordance with standard BAS EN 1603. Measured are values of length, width and thickness before and after exposure to certain conditions.

Bending strength is tested in accordance with BAS EN 12089. For the purpose of handling, products must have a level of bending strength of at least 50 kPa. For this test press is used, whose force is applied to the central part of the test sample, whose edges are fixed on the carriers. Speed of force application on the sample is 10 mm/minute, with a tolerance of ± 10%.

Determination of thermal conductivity was performed on two sheets of each sample of EPS with dimensions 300 x 300 mm and thickness 50 mm and 100 mm. Test sample is heated and temperature on both surfaces of the sample, the hot and cold side, is measured by thermocouples. When a steady state is established, which means that the temperature of the hot and cold side are constant and for a period of 20 minutes, the coefficient of thermal conductivity is calculated. The tests were performed in accordance with standard BAS EN 12667/2005 using instrument LM.305 Lambdametar (Stirolab, Slovenia). Analysis is performed at 10 °C. Control of the instrument is done by internal standard XPA λ=0.0217 W/mK. Standard reference material 1450d is used for calibration of the instrument.

3. RESULTS AND DISCUSSION

Styrofoam or expanded polystyrene (EPS) is material used for thermal and acoustic insulation. It is most commonly used in construction, but it is widely applied as packaging material for various products in the food and electrical engineering industry. The specific mass of foamed polystyrene is in the range of 5 to 300 kg/m^3 and mostly used are materials with a density of 15 to 40 kg/m^3.

Because of an extremely low thermal conductivity of EPS, the heat-insulating properties of EPS are excellent. Thermal properties of EPS depend on the temperature and density. Its thermal conductivity varies depending on the density of the material (the function is not linear). Increasing density of EPS material, thermal conductivity decreases and the material has better insulation properties. When selecting the EPS material, it is important to choose material with appropriate mechanical properties and then achieve good insulation properties by tuning density of the material. Thermal conductivity depends also on the moisture content. Normally, for every percentage of absorbed moisture (by volume), the coefficient of thermal conductivity increases by 3.8% and this in turn means that the thermal insulation properties of the material deteriorate. The linear coefficient of thermal expansion of EPS ranges between 5x10^{-5} K^{-1} to 7x10^{-5} K^{-1}. Increasing density of EPS, resistance to diffusion of water vapor increases. EPS is not soluble in water and it does not absorb water. This characteristic of EPS is practically independent of bulk density, but it depends on the production process, since water may penetrate only through the narrow channels between the cells. This characteristic is extremely important because the minimum amount of water worsens thermal insulating properties of EPS.

Standard BAS EN 13163 defines the requirements for industrial products from expanded polystyrene used for thermal insulation of buildings. Standard describes the characteristics of the products and procedures for testing and conformity assessment, marking and labeling. This Standard also includes products made of polystyrene, which are used for acoustic insulation and in prefabricated thermal insulation systems and composite panels.

Defined by that standard are the properties to be tested for expanded polystyrene:

- thermal resistance and thermal conductivity
- length and width
- thickness
- angularity
- flatness
- stability of the measures
- bending strength.

Most mechanical properties of EPS depend on the density of the material. Important mechanical property of EPS is its compressive strength. EPS with a density of 15 kg/m^3, for example, reaches the elastic limit at 2%. Further load leads to permanent deformation. Physical and mechanical properties of expanded polystyrene (EPS F, EPS 120, EPS 150, EPS200) are tested and results are shown in Table 1.

Table 1. Physical and mechanical properties of expanded polystyrene samples (EPS F, EPS 120, EPS 150, EPS200)

Sample No.	Characteristic		Results			
			EPS F	EPS 120	EPS 150	EPS 200
1.	Dimensions					
	Length	min	99.70 cm	99.5 cm	99.0 cm	29.90 cm
		max	100.0 cm	99.6 cm	100.0 cm	30.00 cm
		average	99.85 cm	99.55 cm	99.95 cm	29.95 cm
	Width	min	49.9 cm	49.70 cm	49.9 cm	29.90 cm
		max	50.0 cm	49.90 cm	50.0 cm	30.00 cm
		average	49.95 cm	49.80 cm	49.95 cm	29.95 cm
	Thickness	min	4.90 cm	4.90 cm	5.0 cm	4.90 cm
		max	5.00 cm	5.00 cm	5.0 cm	4.90 cm
		average	4.95 cm	4.95 cm	5.0 cm	4.90 cm
2.	Bulk density					
		min	13.81 kg/m^3	18.86 kg/m^3	21.77 kg/m^3	28.30 kg/m^3
		max	14.44 kg/m^3	20.38 kg/m^3	25.04 kg/m^3	32.60 kg/m^3
		average	14.16 kg/m^3	19.62 kg/m^3	23.04 kg/m^3	29.90 kg/m^3
3.	Compressive strength at 10 % deformation					
		min	104.15 kPa	122.80 kPa	179.55 kPa	260.90 kPa
		max	108.84 kPa	131.31 kPa	182.82 kPa	272.50 kPa
		average	105.85 kPa	127.52 kPa	181.04 kPa	263.90 kPa
4.	Bending strength					
		min	163.06 kPa	211.0 kPa	219.00 kPa	306.50 kPa
		max	166.56 kPa	224.0 kPa	241.19 kPa	329.20 kPa
		average	166.56 kPa	220.0 kPa	229.12 kPa	315.70 kPa
5.	Tensile strength					
		min	404.00 kPa	352.0 kPa	340.00 kPa	364.0 kPa
		max	588.00 kPa	396.0 kPa	476.00 kPa	396.0 kPa
		average	477.60 kPa	370.0 kPa	396.80 kPa	315.7 kPa
6.	Factor of resistance to water vapour diffusion μ		40	62	100	-
7.	Shear strength					
		min	25.84 kPa	53.2 kPa	53.15 kPa	58.49 kPa
		max	37.06 kPa	55.4 kPa	62.07 kPa	69.69 kPa
		average	31.67 kPa	54.0 kPa	58.41 kPa	65.11 kPa
8.	Lon-term water absorption by immersion					
		min	3.501 %	1.82 %	2.892 %	2.854 %
		max	3.606 %	2.46 %	3.522 %	4.043 %
		average	3.550 %	2.16 %	3.130 %	3.420 %

For all tested samples, physical and mechanical characteristics are in accordance with standards and all samples meet requirements that expanded polystyrene can be used as products for thermal insulation of residential buildings.

One of the most important features is the coefficient of thermal conductivity and resistance to heat transfer of polystyrene. Testing of thermal resistance and thermal conductivity is based on measurements performed in accordance with the requirements of BAS EN 12667 or BAS EN 12393. By performing the test, mean reference temperature should be 10 °C and measured values must be expressed with three significant digits. The coefficient of thermal conductivity, and thus the resistance to heat transfer depend on the density of the EPS and are calculated using following equation.

$$\lambda = \frac{\phi \delta}{A(\vartheta_A - \vartheta_A)} \quad \text{(W/mK)} \tag{1}$$

where is:

− ϕ-heat flux which in steady state passes through the sample plate, W

− A-surface of hot plate, m^2

− δ −sample thickness, m

− ϑ_A-average temperature of hot plate, °C

− ϑ_B –average temperature of cold plate, °C.

The results of thermal conductivity and thermal resistance are shown in Table 2.

Table 2. Values of thermal conductivity measured for expanded polystyrene samples (EPS F, EPS 120, EPS 150, EPS200)

Sample No.	Thickness	Length and width	Bulk density of the sample	Coefficient of thermal conductivity	Thermal resistance
	mm	mm	kg/m^2	W/m^2K	m^2K/W
EPS F					
1.	50	298 x 299	14.6	0.03866	1.29
2.	50	298 x 299	14.2	0.03862	1.29
3.	98	299 x 300	14.0	0.03813	2.57
4.	99	300 x 299	14.0	0.03865	2.56
EPS 120					
1.	49.0	297 x 298	19.39	0.03392	1.44
2.	50.0	298 x 297	19.30	0.03427	1.46
3.	99.2	297 x 297	18.75	0.03511	2.83
4.	99.0	297 x 296	18.56	0.03561	2.81
EPS 150					
1.	50	300 x 300	26.4	0.03407	1.47
2.	50	300 x 299	27.3	0.03391	1.48
3.	100	299 x 300	23.0	0.03434	2.91
4.	101	299 x 300	23.2	0.03422	2.97
EPS 200					
1.	49	299.6 x 299	28.30	0.03232	1.52
2.	49	300 x 300	28.90	0.03242	1.51
3.	99.75	300 x 300	34.98	0.03291	3.03
4.	99.25	300 x 300	28.94	0.03262	3.06

Coefficient of thermal conductivity varied between 0.03232 to 0.03866 W/m^2K and it is slightly influenced by thickness and bulk density of the sample. Measured values of thermal resistance of heat transfer varied between 1.44 to 3.06 m^2K/W. Thermal resistance is increased greatly by increasing the thickness of EPS samples.

4. CONCLUSION

EPS is material that is most used in the construction industry as a thermal insulation product. It can be used in areas with low and high load. The mechanical properties of EPS depend on the density of the material. By increasing the density of EPS, resistance increases to diffusion of water vapor. Since polystyrene is not soluble in water, it does not absorb water. Stability of thermal insulation materials based on EPS depends on the physical and chemical characteristics of polystyrene. Physical and mechanical characteristics of tested EPS samples showed that all samples meet requirements that are needed for use as thermal insulation materials in residential buildings. Thermal conductivity depends slightly on the thickness of the samples whereas resistance to heat transfer depends on the density and thickness of the EPS.

5. REFERENCES

[1] J. Mack, B. G. Frushor, J. R. Kontoff, H. Eichenauer, K. H Ott, C. Schade, *Polystyrene and styrene copolymers*, Ullmanns Encyclopedia of Industrial Chemistry, Wiley- VCH Weinheim, 2007.

[2] B. Raenby, *Basic reactions in the photodegradation of some important polymers*, J Macromol Sci Pure Appl Chem., Vol. 30 (1993) 583−594.

[3] H. Mark, N. M. Bikales, C. G. Overberge, *Encyclopedia of Polymer Science and Engineering*, 2nd Ed. Vol I, J. Wiley and Sons, New York, 1985.

[4] R. Raj, A. K. Nayak, M. A. Akbari, P. Saha, *Prospects of expanded polystyrene sheet as green building material*, Int J Civil Eng Res, Vol. 5 (2014) 145−150.

[5] M. Chanda, S. K. Roy, *Plastics Tehnology Handbook*, Marcel Dekker, New York, 1987.

[6] W. Dawid, T. C. Wallace, *Polystirene and styrene copolymers*, Appl Polym Sci, Vol. 285 (1989) 363−382.

[7] R. Skochdopole, G. Welsh, *Polystyrene foams in structure polymers*, Encycl Polym Sci Eng, 16 (1989) 210−216.

[8] J. Scheirs, D. Priddy, *Modern styrenic polymers, Polystyrenes and styrenic copolimers*, Wiley, 2003.

[9] M. Beghmans, K. C. Bleijenberg, *Foaming polystirene beads: new perspective on a thermoplastics foam*, Society of Petroleum Engineering – 5th International. Conference on Thermoplastic Foam, Chicago, USA, 2006, 20−24.

[10] F. Cullis, *Thermal Stability and Flammability of Organic Polymers,* Br Poly J, Vol. 16 (1984) 253−257.

УТИЦАЈ ФИЗИКАЛНИХ КАРАКТЕРИСТИКА НА ТЕРМИЧКУ ПРОВОДЉИВОСТ ИЗОЛАЦИОНИХ МАТЕРИЈАЛА НА БАЗИ ПОЛИСТИРЕНА

Сажетак: Захваљујући разноликости примјене, једноставној прерадљивости и релативно ниској цијени, полимери на бази полистирена су веома широко распрострањени термопластични материјал. Око 45% произведеног полистирена се производи као компактни и пјенасти производ. Целуларни пјенасти полистирен може се произвести као експандирани (EPS) и екструдирани (XPS) полистирен, а највише се користи као изолациони материјал. Физикално-хемијске карактеристике експандираног и екструдираног полистирена су од посебне важности за термичку проводљивост материјала. У овом раду су испитиване четири врсте полистирена. Коефицијент термичке проводљивости и отпорност трансферу топлине мјерене су и упоређиване са механичким особинама материјала. Потврђена је зависност отпорности трансфера топлине у односу на густоћу и дебљину испитиваног полистирена.

Кључне ријечи: полистирен, термичка проводљивост, трансфер топлине.