Assessment of Strength under Compression of Expanded Polystyrene (EPS) Slabs

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The data obtained in testing expanded polystyrene (EPS) slabs subjected to short-term compression are discussed. The results demonstrated that the compressive strength of the slabs should be determined according to critical stress taking into account the type of deformations shown in the stress-strain diagram. The regression equations are provided for calculating the compressive stresses at 10 % relative deformation and for critical stress of EPS slabs with the density ranging from 12 to 44 kg/m^3.

Keywords: expanded polystyrene (EPS) slabs, compression, deformation, compressive stress, conditional strength, critical stress.

INTRODUCTION

Compression is one of the main stressed states of polystyrene foam (expanded polystyrene) used as a thermal insulating material in construction.

The type of deformation and failure of polystyrene foams depend on the structure and physical characteristics of the polymer used as a basic material and on the strength of the particular elements of the macrostructure under compression. The macrostructure of foam plastics (polystyrene foam) consists of closed cells. The main part of its mass is concentrated at the nodes and junctions of the cells [1 – 3]. The deformations and the failure of the material under compression occurs ossording to the stress-strain diagram [3 – 6]. Different mechanical states are marked by leg points *A*, *B*, *C* (Fig. 1) on the graph representing the compression of expanded polystyrene samples. Table 1 gives the stress and the corresponding mechanical states of expanded polystyrene slabs.
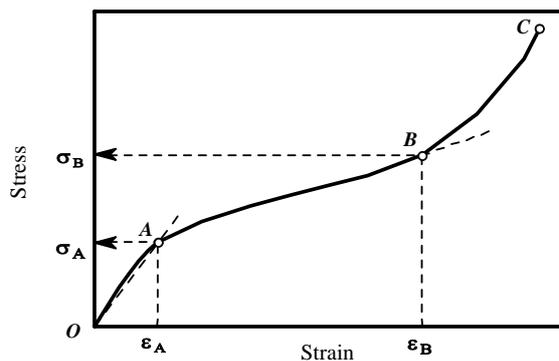
Fig. 1. A scheme of expanded polystyrene under short-term compression [3 – 5]

Mechanical characteristics (the ordinates of the compression graph) determine the ability of expanded polystyrene slabs to resist compressive forces aimed to deform and disrupt them. The abscissas of the compression diagram characterise the ability of slabs to be deformed to a certain extent.

Table 1. Mechanical characteristics of expanded polystyrene slabs under short-term loading

Stress (see Fig. 1)	Corresponding stress and its conventional signs
σ_A, corresponding to the end point of the section *A*	Ultimate (critical) stress σ_{cr} [*) (when this value is not exceeded, the linear or similar relationship is found between stress and strain)
σ_B, corresponding to the attenuation of flexural deformations of cell walls when their stability is lost	Stress corresponding to maximum possible compaction σ_{comp} of the damaged elements of polystyrene macrostructure
Exceeding the value of σ_B, corresponding to the "flattening" of polystyrene when the elements of macrostructure are damaged	Stress is not a mechanical characteristic of EPS slabs subjected to compression

[*) stress is referred to as in [4, 5]

In testing EPS slabs for mechanical behaviour, their clear expressed strength has not been defined. This should be taken into account in specifying the allowable loads on the above products. The strength of the macrostructure is changed at a particular critical stress σ_{cr} when the behaviour of the cellular structure elements changes (see stress σ_A). When stress exceeds σ_{cr}, the residual deformation of expanded polystyrene develops.

If such changes occur in the construction enclosures made of these elements during their service life, it may have grave consequences. As far as EPS slabs are concerned, the ultimate stress which they can withstand without failure of their macrostructure should be known. This is stress σ_A (σ_{cr}) corresponding to the end portion of the segment *OA* (see Fig. 1), and its value should be used to evaluate the compressive strength of expanded polystyrene slabs as load-bearing elements.

Recently, a method of determining the strength of expanded polystyrene slabs by a conditional value of a compressive stress calculated on the basis of 10 % deformation has become widely used in practice due to its simplicity and it can be found in specifications [7, 8]. This

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value may be used at the stage of determining optimal technological parameters of slab manufacture when the influence of such factors as the raw materials used, density and methods of manufacture should be assessed. However, if EPS slabs are used as structural or heat-insulating materials, the value of σ_{cr} expressing their compression strength should be defined more precisely.

The purpose of this research was to assess the impact of expanded polystyrene slab density on its compression stress at 10 % relative deformation and critical stress based on the data obtained in a large number of tests.

EXPERIMENTAL

The compression strength of expanded polystyrene was tested using slabs manufactured at Lithuanian enterprises by foaming in a closed space hard granules of 0.9 – 2.5 mm in diameter supplied by the companies "Styrochem" (Finland), BASF (Germany) and "Dwory" S. A. (Poland).

The cubic specimens with (50 ± 1) mm long rib, cut out of 50 mm thick slabs (as a product commonly used for thermal insulation and structural purposes) were tested. The character of deformation of polystyrene specimens under short-term loading was determined according to [9]. The compression load was assumed to be perpendicular to the surface of the slab of which the samples were cut out. The rate of loading was $(4 – 6)$ mm/min. The loading was continued until 10 % strain of the sample was reached. Height of the samples was taken as gauge length for determination of strain. The deformation was measured to the accuracy of 0.01 mm. The stress-strain relationship was plotted for the samples tested and the values of the ultimate stress σ_{cr} corresponding to the sharp decrease of the initial sample rigidity (by drawing the graph of the deformation differences [10] were determined. Stresses, corresponding to 5 % and 10 % deformations, were also calculated according to [9].

The mean values of σ_{10} and σ_{cr} (in kPa) were expressed with term of density by the linear relationships of the form:

$$\overline{\sigma} = b_0 + b_1 \cdot \rho, \tag{1}$$

where ρ is the EPS density, kg/m³; b_0, b_1 are the constant ratios calculated from the testing results by the least squares method [11]. Linear relationships were used because of their relative simplicity and sufficient accuracy.

The correlation coefficient $R_{\sigma \cdot \rho}$ shows how close is the relation between two variables in a regression scheme with linear relationship. To interpret the values adopted by it, a so-called determination coefficient showing the extent of variation of a considered parameter depending on the variation of EPS density is used. The above coefficient measures the portion of σ determined by ρ, thereby directly expressing the variation of an output value, depending on the controlled input parameters. When the linear relationship is found, a determination coefficient is the square correlation coefficient $R_{\sigma \cdot \rho}^2$, which indicates the impact of a particular parameter (in this case, EPS density) on a resulting characteristic [12].

To determine the spread of the strength values over the regression line defining the values σ_{10}, σ_{cr}, the mean square deviation S_{tar} (an absolute value of an average deviation of test data from the empirical regression line which is constant at all its segments) determined according to [13] was used.

The predicted allowable least value of the strength parameter $\sigma_{10.p}$ or $\sigma_{cr.p}$ is presented here as the lower confidence limit of its quantile $p = 0.90$, with the probability $(1 - \alpha) = 0.90$ [7]

$$\sigma_p = \overline{\sigma} - k \cdot S_{tar}, \tag{2}$$

where k is the allowable multiplier for one-sided confidence limit of the quantile $p = 0.90$, with the probability $(1 - \alpha) = 0.90$, based on the volume of sample and determined according to [7].

RESULTS AND DISCUSSION

The existence of the relationship between stresses and strains of EPS slabs becomes evident from the results obtained in the repeated loading of samples. In Fig. 2 one can see the development of residual deformations (not recovering quickly after the load is removed) under the repeated loading when the compressive stress is higher or lower than the value of σ_{cr}. When the repeated compressive stress is equal to σ_{10} and σ_5 (corresponding to 10 % and 5 % deformation of the samples), the residual deformations after 11 loading cycles are $\varepsilon_{res} = 7.3$ and 3.4 %, respectively. When the compressive stress is $(1 – 1.2)\sigma_{cr}$, the residual deformations make about 0.6 %, i.e. being by $(6 – 12)$ times lower than those found in the
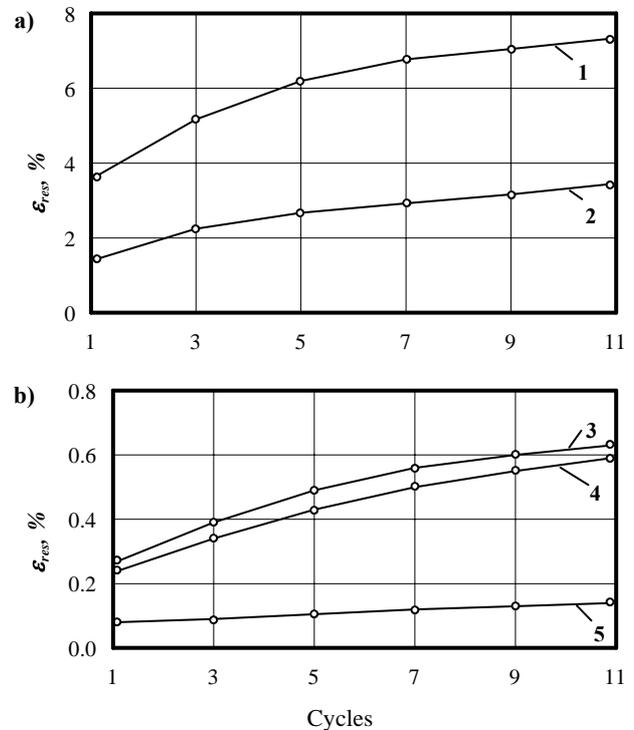
Fig. 2. The develomp ment of residual deformations in expanded polystyrene with the density of 14 kg/m³: a – under cycling compressive stress equal to: $1 – \sigma_{10}$; $2 – \sigma_5$, b – the same for: $3 – 1.2\sigma_{cr}$; $4 – \sigma_{cr}$; $5 – 0.8\sigma_{cr}$

first case. The low value of the residual deformation (not exceeding 0.2 %) was observed after 11 loading cycles, with the compressive stress being $0.8\sigma_{cr}$. Thus, it may be stated that the values of the residual deformations, when the compressive stress is less than σ_{cr}, and when it is more than σ_{cr}, differ considerably. If, in the first case, the deformations are relatively small (not exceeding 0.6 %), than, in the second case, they are much larger. Higher values of residual deformations indicate that the performance of expanded polystyrene slabs has changed.

The experimentally determined empirical relationships between strength characteristics of expanded polystyrene slabs and their density under compression σ_{10} and σ_{cr} are presented in Fig. 3 – 5.

Stress values corresponding to 10 % compression deformation of sample EPS slabs depending on their density are presented in Fig. 3. The empirical regression equation of the mean values σ_{10} depending on EPS density can be presented as following:

$$\overline{\sigma}_{10} = 8.4 \cdot \rho - 54.6, \qquad (3)$$

with the mean square deviation reaching $S_{tar} = 5.8$ kPa and determination coefficient $R^2_{\sigma \cdot \rho} = 0.964$, showing that the range of the values $\overline{\sigma}_{10}$ depends by about 96.4 % on density variation of the material and by only 3.6 % on other factors.
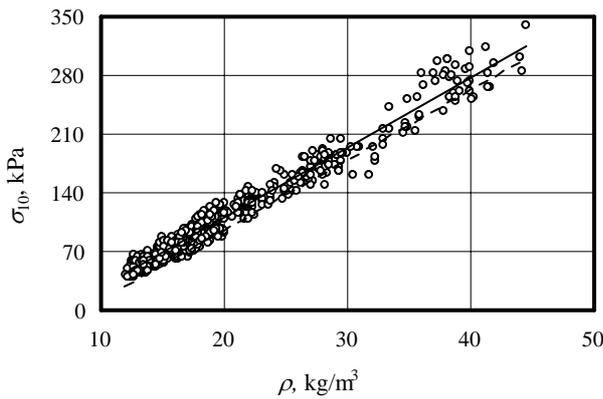
Fig. 3. The stress corresponding to 10 % deformation of expanded polystyrene slabs under compression, depending on their density. o – experimental values; the continuous line – the empirical regression line of the mean stress value according to slab density; the dotted line – the same for the predicted stress value according to the slab density

In assessing the expected least value of $\sigma_{10.p}$, the expression (2) should be used assuming the coefficient $k = 1.346$ (with the number of tests equal to $n = 1011$), which was determined according to [7]. In this case, $k \cdot S_{tar} = 7.8$ kPa, while a regression equation for the expected least values of $\sigma_{10 \cdot p}$ depending on EPS density is

$$\sigma_{10.p} = 8.4 \cdot \rho - 62.4. \qquad (4)$$

This relationship is plotted as a dotted line in Fig. 3.

In Fig. 4, the mean values of $\overline{\sigma}_{10}$ and $\sigma_{10.p}$ calculated from the equations (3) and (4), respectively, as well as from the analogical regression equations according to the standard LST EN 13163 are given. As one can see in

Fig. 4, expanded polystyrene slabs with the density up to 19 kg/m³ manufactured in Lithuania satisfy the specified values for $\overline{\sigma}_{10}$ [7], however not reaching them at higher densities. Thus, when the density is 20 kg/m³ or 30 kg/m³, these values are lower than specified by 4.7 % or 9.9 %, respectively. The predicted lowest values of $\sigma_{10.p}$ for polysterene foam slabs with the density ranging from 12 to 30 kg/m³ satisfy the requirements [7].
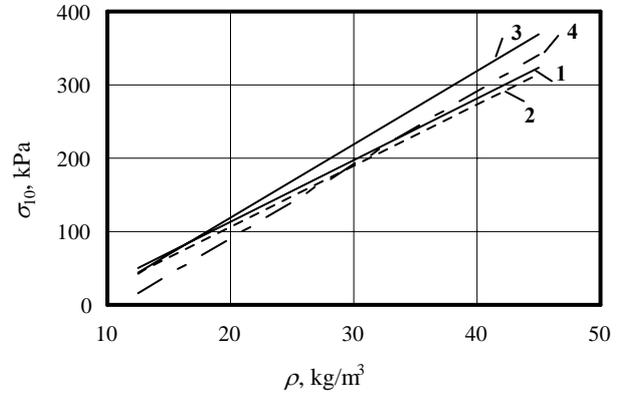
Fig. 4. The empirical lines of the values of stress corresponding to 10 % deformation of expanded polystyrene slabs under compression, depending on their density. Lines 1, 2 – mean and predicted stress values for slabs manufactured by Lithuanian enterprices; 3, 4 – the same according to the data provided in [7]

The values of critical stresses under compression for expanded polystyrene (EPS) slabs manufactured in Lithuania are presented in Fig. 5. The empirical regression equation of the mean values of $\overline{\sigma}_{cr}$ according to polysterene density is:

$$\overline{\sigma}_{cr} = 5.8 \cdot \rho - 43.9, \qquad (5)$$

with $S_{tar} = 12.9$ kPa and determination coefficient $R^2_{\sigma \cdot \rho} = 0.882$, showing that the ranging of $\overline{\sigma}_{cr}$ depends by about 88 % on the material density and by 12 % on other factors (the methods of analysis in particular) [10].

To assess the expected lowest value of $\sigma_{cr.p}$, the expression (2) should be used, assuming $k = 1.356$ when $n = 656$ [7]. When $k \cdot S_{tar} = 17$ kPa, the regression equation for the predicted critical stress values according to polystyrene density is:

$$\sigma_{10.p} = 5.8 \cdot \rho - 61.4. \qquad (6)$$

This relationship is plotted as a dotted line in Fig. 5.

The value of the critical stress approaches that found in the samples deformed by 5 %, but does not reach it. An additional analysis of the experimental data obtained has shown that the relationship between stresses σ_{10}/σ_5 is about 1.18 ($n = 265$; $s = 0.05$), with EPS density ranging from 12 to 44 kg/m³.

Thus, the deformation of the samples grows from 5 % to 10 %, i.e. twice, when the compression increases only by about 18 %. We think that, under these conditions, the spread in values of $\sigma_{10\%}$ largely depends on whether a constant rate of sample loading can be maintained.

It may be useful to consider the relationship between the critical stress σ_{cr} of expanded polystyrene slabs under
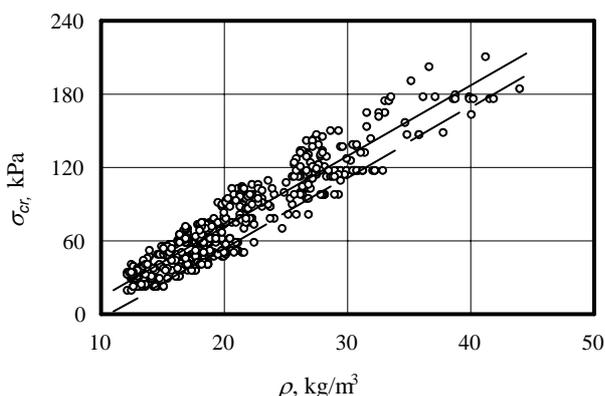
Fig. 5. The dependence of the critical stress developed in expanded polystyrene slabs under compression on their density. **o** – experimental values; the continuous line – the empirical regression line of the critical stress value according to slab density; the dotted line – the same for the predicted stress value according to slab density

compression and the stress occurring when they are deformed by 10 %, i.e with the value assumed as a conditional strength parameter [7, 8]. The relationship σ_{cr}/σ_{10}, with EPS density ranging from 12 to 44 kg/m^3 has been determined as approximately reaching 0.60 ($n = 265$; $s = 0.08$). It can be observed that the stress σ_{10} is determined beyond the critical range when the rigidity of material is decreasing (see Fig. 1). Therefore, the assessment of the strength under compression of expanded polystyrene (EPS) slabs according to the value of σ_{10} cannot be considered completely reliable and may lead to errors. Hence, taking into account the above considerations, the value of critical stress may be recommended to be used for more precise evaluation of the strength under compression of EPS slabs.

CONCLUSIONS

1. Brittle failure of expanded polystyrene (EPS) under compression is not observed and, therefore, its ultimate strength cannot be accurately determined. The characteristic of compression behaviour is often defined conditionally as a stress corresponding to 10 % deformation of specimens. The macrostructure of EPS with different density is tolerant to large deformations under compression which develop at various speed when the specific load is increased. A breaking point can be observed on the stress-strain diagram indicating the beginning of the failure of EPS macrostructure. The maximum stress causing the initial failure of polystyrene macrostructure and determining its ultimate compression strength is referred to as critical stress in accordance with [4, 5].
2. The stresses corresponding to 10 % compression strain for expanded polystyrene slabs of various density may be obtained from the regression equations. The values of $\sigma_{10, p}$ predicted for EPS slabs with density ranging from 12 to 30 kg/m^3 satisfy the requirements of the standard LST EN 13163:2003 (EN 13163:2001).

3. The critical stress of expanded polystyrene slabs under compression depends on their density and may be obtained from the empirical equations. The relationship between the stresses σ_{cr}/σ_{10} for EPS slabs, with the density ranging from 12 to 44 kg/m^3, is approximately 0.60. This value may be relied upon in determining the ultimate strength of the slabs under compression, when the value of $\overline{\sigma}_{10}$ is obtained according to the expression $\overline{\sigma}_{cr} = 0.6\,\overline{\sigma}_{10}$.

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