Prediction of Creep Strain of the Expanded Polystyrene (EPS) in Long-term Compression

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The creep compliance of expanded polystyrene (EPS) slabs was studied with the aim of developing a simple way for prediction of long-term creep strain. The prediction of creep strains was carried for 10 years for specimens, which were subjected to long-term compression of $\sigma_c = 0.35\sigma_{10\%}$. The results were obtained in determining creep strains of the specimens of expanded polystyrene slabs with density ranging from 15.5 kg/m^3 to 35.5 kg/m^3. The total time of testing was 988 days. The prediction of creep compliance development for the period of 10 years was made by extrapolation based on power and exponential regression equation applied to approximate creep formation. Predictions obtained by using power and exponential equations were synthesised. A relationship between the creep compliance and EPS density for the investigated material is revealed.

Keywords: expanded polystyrene slabs (EPS), long-term creep, creep compliance, prediction.

INTRODUCTION

The expanded polystyrene (EPS) slabs are used as constructive thermal insulation material. Most often they are used for thermal insulation, packing and road embankments [1 – 3]. One of the main features that characterize this material is their density. If the density of the expanded polystyrene is known, thermal and strength properties of this material may be approximately predicted [4].

The exploitation of expanded polystyrene products used in building application and road embankments in most cases is associated with compressive load, where its mechanical strength is very important [3, 5, 6]. A valuable property of expanded polystyrene (EPS) is its creep strain resistance. Therefore, the time-dependent mechanical (creep strains) behavior of these products has been a topic of significant interest for many years [5 – 8].

The EN standard [9] on thermal insulation material describes a method for determining stress values with respect to creep behavior when expanded polystyrene is subjected to the sustained compressive loads. The basis for the mathematical treatment of the system is the Findley equation. Many authors propose the simplified power Findley equation for making long-term prediction of the creep strain development in expanded polystyrene [6 – 8].

Some investigators have been concerned with other mathematical equation in order to predict long-term creep strains behavior of the expanded polystyrene [10 – 13]. The comparison between the Findley equation and other mathematical models in these articles are presented.

Therefore, the research on EPS strength and deformation characteristics is a matter of urgency in order to get the maximal benefit of bearing properties of this material. The investigations should be conducted in the field of changes in strength and deformation of material under short- and long-term compressive loading.

The aim of the present investigation is to select an optimal mathematical model that is able to describe most precisely the nature of expanded polystyrene (EPS) deformation in the course of direct creep experiment and to evaluate quantitatively the further EPS deformability within the whole given period of prediction.

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EXPERIMENTAL

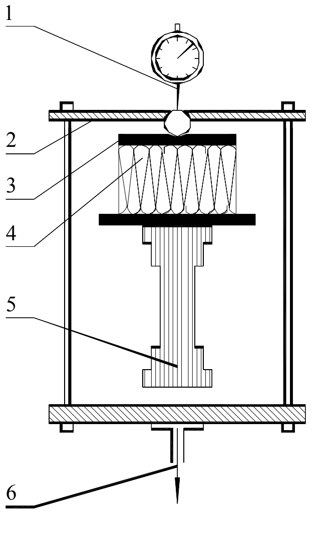
As the object of study is chosen expanded polystyrene (EPS), which is the most typical mass product of constructional thermo-insulating assignment. For investigations the expanded polystyrene slabs of types EPS80–EPS250 [14] with the density of 15.9 kg/m^3 – 35.5 kg/m^3, produced by the Lithuanian manufacturers by volume expansion of solid granules ∅ 0.9 mm – 2.5 mm of raw expandable polystyrene, were used.

The curves of creep strain of the expanded polystyrene were obtained for cubic specimens with 50 mm edge at the special stands [14] (see Fig. 1), providing the development of stress for long period of time (122 – 988 days). The creep strains value was determined by according to the specifications [14], at a static stress $\sigma_c = 0.35\sigma_{10\%}$ (the stress $\sigma_{10\%}$ was determined according to [15]). The error of stabilization in the long-term compressive stress was no more than 1 %, and measurement of creep strains – 0.005 mm. Each experiment of eighteen tests was made on three specimens of the same density. Also every expanded polystyrene specimen was loaded during 15 s according to [9]. The starting point of the creep was assumed the strain within (60 ±5) s after the beginning of loading. Long-term experiments were carried out in a room with temperature of (23 ±2) °C and relative air humidity of (50 ±5) %.

The values of creep strains $\varepsilon_c(t)$, %, of the expanded polystyrene were calculated according to formula:

$$\varepsilon_c(t) = \frac{\bar{X}_c(t)}{\bar{d}_s} 100\,\%, \qquad (1)$$

where $\bar{X}_c(t)$ is the average decrease in the thickness of specimens at the moment of time t, mm; $\bar{d}_s$ is the average thickness of the specimens under the preload of 250 Pa, mm.



a

b

Fig. 1. The schematic of the device for determining the creep strains of expanded polystyrene (EPS) a): 1 – dial gauge; 2 – loading suspension; 3 – movable plate for uniform distribution of loading; 4 – test sample; 5 – support beam; 6 – invariable load; b) a general view of the device for test

In the further step a creep strain value was formulated, as creep compliance $J_c(t)$, which is only function of time:

$$J_c(t) = \frac{\varepsilon_c(t)}{\sigma_c}, \quad (2)$$

where $J_c(t)$ is the value of creep compliance at time moment t, MPa^{-1}; σ_c is the constant compressive stress, MPa; t is the time of reading.

In work of the phenomenological description of function $F[J_c(t)]$ of the expanded polystyrene (EPS), it has been achieved using two assumptions.

According to the first assumption, creep is the steady-state process and can be described by the equation [8, 9]:

$$\bar{J}_c(t) = b_0 t^{b_1}, \quad (3)$$

where $\bar{J}_c(t)$ is the average value of creep compliance at time moment t, MPa^{-1}; b_0, b_1 are the constants related to properties of materials; t is time in days.

According to the second assumption, creep is a damped process and the relationship between a creep compliance $\bar{J}_c(t)$ and time t is exponential [16, 17]:

$$\bar{J}_c(t) = b_0\left[1 - \exp\left(-b_1 t^{b_2}\right)\right], \quad (4)$$

where b_0 is the $\bar{J}_c(t)$ value, when $t \to \infty$; b_1, b_2 are the constants related to properties of materials; t is time in days.

The constant factors of the empirical relationships (3) and (4) – "creep compliance – duration of the compressive stress σ_c" were calculated by the least square method [18, 19]. For the deviation of test data values over the regression lines (3) and (4) was assumed the mean square deviation S_r, which was determined according to [18, 19].

The determination coefficient $\eta^2_{J_c \cdot t}$ [20] showing the dependence of creep compliance $J_c(t)$ variation on the variation of t was assumed to be an indicator of the interrelationship of the variables $J_c(t)$ and t in the non-linear regressions (3) and (4).

RESULTS AND ANALYSIS

In Fig. 2, the curves of reduction in the thickness $\bar{X}_c(t)$ of the expanded polystyrene samples under influence of the fixed compressive load are submitted. The creep strains $\varepsilon_c(t)$, %, of the expanded polystyrene were calculated according to (1), further they were submitted as the relative value according to equation (2). The results are presented in Fig. 3.

The results of long-term compression of the expanded polystyrene received in carried out tests are given in Table 1. The values of the invariable parameters b_0, b_1 from Eq. (3) and b_0, b_1, b_2 from Eq. (4), as well as mean square deviation and determination coefficient are also given in this table. As shown by statistical analysis of test results, the creep compliance of the expanded polystyrene approximated by the regression equation (3) and (4) represents the obtained data equally well, taking into account testing error (see continuous and dashed lines on the Fig. 3). Therefore, it was hardly possible to give preference to any of the above relationships in the tests performed.

In Fig. 4 deviations between the average values ($\bar{J}_c(t) = (t = 50)$), calculated on the equations (3) and (4), from the predicted values of creep compliance $\bar{J}_c(t)$ presented in the Table 1 are submitted. The deviations of the average values ($\Delta\bar{J}_c(t = 50)$) have been calculated according to the formula:

$$\Delta\bar{J}_c(t = 50) = \frac{\bar{J}_{c(3)}(t = 50) - \bar{J}_{c(4)}(t = 50)}{\bar{J}_{c(3)}(t = 50)} 100\,\%, \quad (5)$$

where $\bar{J}_c(t = 50)_{(3)}$ and $\bar{J}_c(t = 50)_{(4)}$ are the creep compliance of the expanded polystyrene for $t = 50$ years (see Table 1), calculated according to equations (3) and (4).

It should be noted that, the divergence between the predicted values of the creep compliance (see Fig. 4

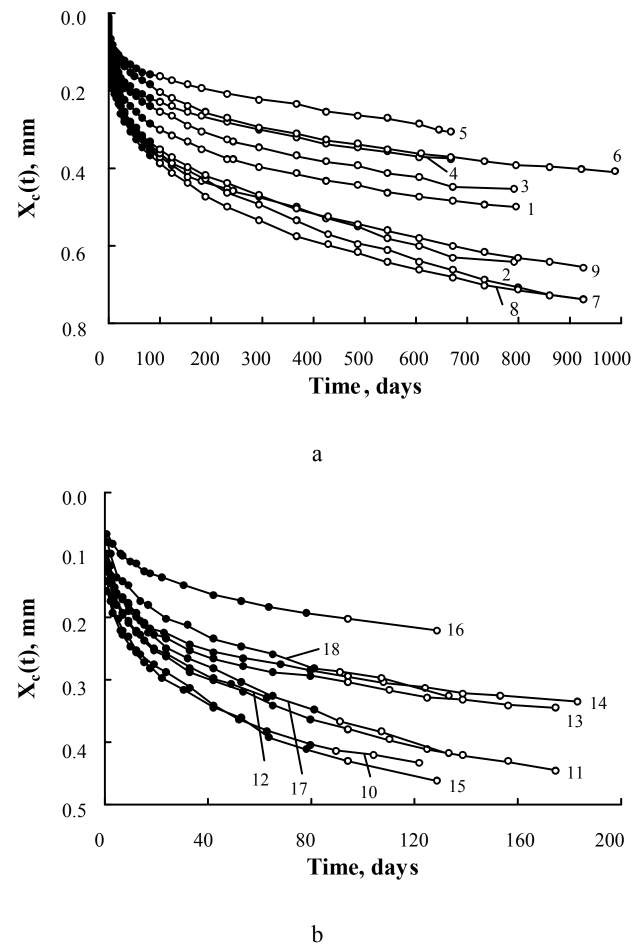


Fig. 2. The reduction of thickness of expanded polystyrene specimens subjected to a fixed compressive stress of $\sigma_c = 0.35\sigma_{10\%}$ for 90 days (●) or more than for 90 days (○): a – experimental time-scale up to 988 days; b – experimental time-scale up to 183 days. The test numbers are indicated according to Table 1

$\Delta\bar{J}_c(t=50)$), calculated on the equations (3) and (4) on the average equal to +18.7 % (except two deviations $\Delta\bar{J}_c(t=50)$, the difference makes (30 − 43) %). We should notice that, the extrapolation is based on a number of assumptions (duration of experiment, the minimum number of supervision, etc.) in practice of calculations such usually accept confidential probability of 80 % − 90 % [21].

The certain distinctions of values of the creep compliance (see Fig. 4 $\Delta\bar{J}_c(t=50)$) allow asserting, that the received predictions of results according to the equations (3) and (4) consecutive each other, and they are compatible.

The average values of synthesized $\bar{\bar{J}}_c(t_i)$ for the expanded polystyrene samples are given in Fig. 5. It is necessary to pay attention that the received average values of synthesized estimations of prediction $\bar{\bar{J}}_c(t_i)$, guarantee the highest authenticity of the received results, comparing with the individual results [22].

Using the average values of synthesized prediction $\bar{\bar{J}}_c(t_i)$ (upon joining of individual values of prediction according to equations (3) and (4) together with their

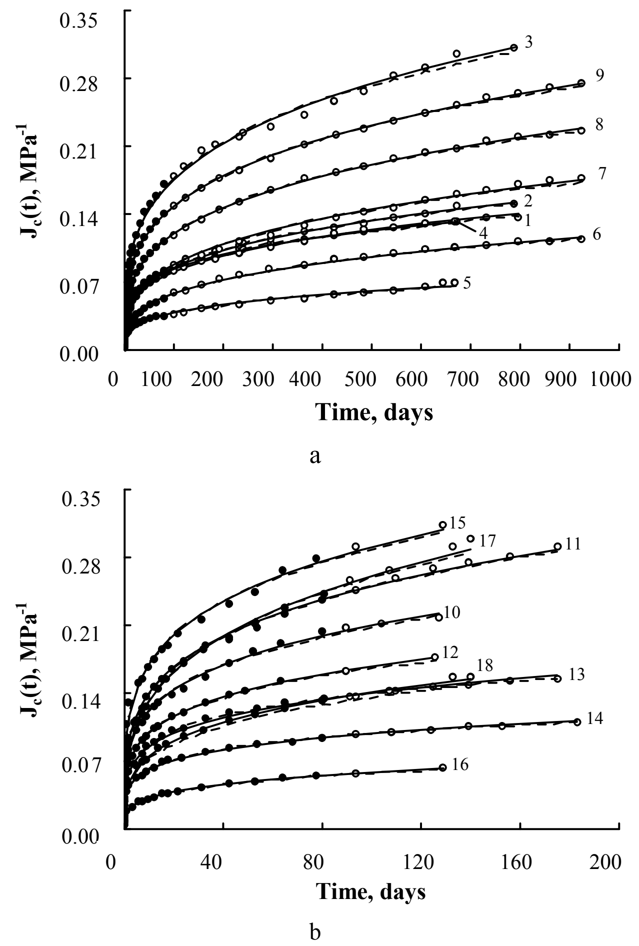


Fig. 3. The development of creep compliance in expanded polystyrene specimens of various densities under fixed compressive stress of $\sigma_c = 0.35\sigma_{10\%}$ for 90 days (●) or more than for 90 days (○): a – experimental time-scale to 988 days; b – experimental time-scale to 183 days. (—) approximation by equation (4) and (- - -) approximation by equation (5). The test numbers are according to Table 1

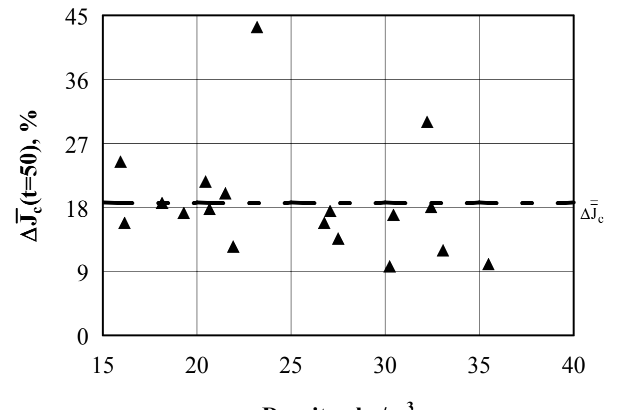


Fig. 4. The deviations of creep compliance ($\Delta\bar{J}_c(t=50)$) at the moment for the time of 50 years calculated from equations (3) and (4)

inaccuracies [22]), a possibility to predict of expanded polystyrene was determined creep compliance considering the impact of density of material. In this case the creep compliance measure is approximated by the regression equation (see Fig. 5, a, continuous line):

Table 1. The experimental data on the deformability of expanded polystyrene specimens under a long-term constant compressive load $\sigma_c = 0.35\sigma_{10\%}$

Test	Results from testing specimens under short- and long-term compressive loads							Results of regression analysis[**)]					Predicted creep compliance $\bar{J}_c(t)$, MPa^{-1}, (years)	
	$\sigma_{10\%}$, kPa	ρ, kg/m^3	$\bar{d}_s$, mm	σ_C, kPa	ε_0,[*)] %	$\varepsilon_C(t)$, %	t, days	b_0	b_1	b_2	S_r	$\eta^2_{J_c \cdot t}$	10	50
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	213	32.2	48.6	74.9	0.802	0.645	122	0.0213/0.2306	0.2955/0.0934	–/0.3383	0.0010/0.0007	0.9986/0.9992	0.241/0.179	0.388/0.213
						1.030	797	0.0234/0.2582	0.2681/0.0841	–/0.3298	0.0018/0.0007	0.9981/0.9997	0.211/0.185	0.326/0.228
2	175	26.8	49.0	61.6	0.820	0.541	122	0.0228/0.3405	0.2837/0.0681	–/0.3097	0.0009/0.0009	0.9987/0.9989	0.234/0.197	0.370/0.258
						0.925	790	0.0229/0.5267	0.2835/0.0420	–/0.3115	0.0011/0.0013	0.9993/0.9992	0.235/0.220	0.370/0.311
3	121	20.7	48.3	42.6	0.918	0.808	122	0.0458/0.7649	0.2976/0.0601	–/0.3235	0.0018/0.0021	0.9990/0.9987	0.526/0.440	0.850/0.583
						1.329	790	0.0486/0.9547	0.2788/0.0489	–/0.3108	0.0041/0.0041	0.9979/0.9980	0.479/0.445	0.749/0.615
4	164	30.2	49.2	57.3	0.914	0.491	122	0.0284/0.2852	0.2306/0.1039	–/0.2562	0.0008/0.0006	0.9989/0.9992	0.189/0.163	0.273/0.206
						0.762	670	0.0274/0.6212	0.2417/0.0438	–/0.2591	0.0014/0.0017	0.9986/0.9978	0.219/0.191	0.294/0.265
5	255	35.5	49.3	89.3	0.828	0.352	122	0.0115/0.2034	0.2568/0.0576	–/0.2739	0.0004/0.0004	0.9983/0.9983	0.095/0.085	0.143/0.116
						0.622	670	0.0104/0.3688	0.2836/0.0276	–/0.3004	0.0014/0.0016	0.9946/0.9932	0.107/0.102	0.168/0.151
6	201	30.4	50.0	70.5	0.791	0.437	124	0.0146/0.3577	0.2935/0.0410	–/0.3091	0.0012/0.0014	0.9951/0.9939	0.162/0.145	0.261/0.205
						0.821	988	0.0140/0.3964	0.3096/0.0330	–/0.3423	0.0014/0.0016	0.9984/0.9982	0.178/0.167	0.293/0.243
7	244	33.1	48.5	85.6	0.962	0.797	123	0.0229/0.4006	0.2912/0.0576	–/0.3144	0.0007/0.0009	0.9993/0.9990	0.250/0.213	0.399/0.287
						1.523	926	0.0212/0.8207	0.3091/0.0246	–/0.3316	0.0020/0.0027	0.9985/0.9975	0.268/0.257	0.441/0.388
8	190	28.5	49.2	66.5	0.948	0.839	123	0.0319/0.5567	0.2857/0.0581	–/0.3075	0.0008/0.0010	0.9995/0.9993	0.333/0.312	0.528/0.387
						1.504	926	0.0315/0.8573	0.2897/0.0352	–/0.3168	0.0010/0.0015	0.9998/0.9995	0.340/0.323	0.542/0.468
9	138	21.9	48.9	48.6	0.913	0.763	123	0.0417/0.6718	0.2749/0.0631	–/0.2966	0.0010/0.0014	0.9995/0.9990	0.398/0.373	0.620/0.461
						1.338	926	0.0412/1.0689	0.2776/0.0372	–/0.3025	0.0012/0.0022	0.9988/0.9993	0.402/0.384	0.629/0.551
10	110	19.3	50.9	39.0	1.73	0.85	122	0.0710/1.0681	0.2354/0.0681	–/0.2520	0.0035/0.0040	0.9968/0.9959	0.490/0.445	0.716/0.592
11	90.1	18.2	48.6	31.6	1.08	0.92	175	0.0789/1.2396	0.2506/0.0639	–/0.2733	0.0043/0.0045	0.9973/0.9972	0.617/0.560	0.923/0.752
12	120	21.5	51.2	41.7	1.67	0.64	126	0.0588/0.7528	0.2280/0.0813	–/0.2423	0.0015/0.0018	0.9986/0.9982	0.382/0.337	0.551/0.440
13	128	23.2	49.9	44.6	1.00	0.69	175	0.0515/0.2543	0.2174/0.2163	–/0.2843	0.0030/0.0018	0.9954/0.9984	0.307/0.227	0.435/0.247
14	171	27.1	50.8	59.8	1.68	0.66	183	0.0383/0.3661	0.2049/0.1093	–/0.2287	0.0013/0.0012	0.9981/0.9985	0.206/0.187	0.286/0.236
15	84.6	16.2	49.8	29.6	0.90	0.93	129	0.0995/1.5979	0.2329/0.0637	–/0.2478	0.0053/0.0063	0.9958/0.9946	0.672/0.615	0.978/0.824
16	206	32.4	48.6	72.2	0.64	0.46	129	0.0176/0.3420	0.2606/0.0521	–/0.2762	0.0007/0.0008	0.9984/0.9977	0.149/0.135	0.227/0.186

Table 1 (continued)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
17	84.9	15.9	48.3	29.7	0.62	0.87	133	0.0670 / 1.4144	0.2951 / 0.0477	– / 0.3144	0.0037 / 0.0046	0.9981 / 0.9973	0.754 / 0.660	1.213 / 0.916
18	123	20.5	48.4	43.2	0.70	0.68	133	0.0402 / 0.7355	0.2724 / 0.0533	– / 0.2915	0.0026 / 0.0029	0.9967 / 0.9960	0.376 / 0.334	0.583 / 0.456

*) is the relative strain (after 60 s from the beginning of loading).
**) the values in the numerator and denominator are calculated by Eqs. (3) and (4) correspondingly.

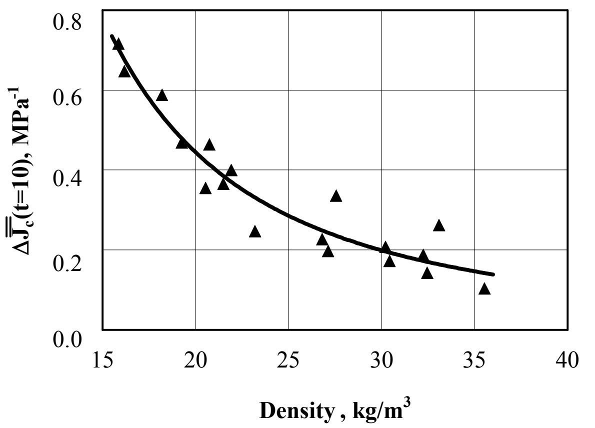


Fig. 5. The dependence of average values of synthesized estimations of creep compliance predictions $\overline{\overline{J}}_c(t_i)$ of expanded polystyrene (EPS) on the density ρ at a fixed compressive stress $\sigma_c = 0.35\sigma_{10\%}$ operating for 10 years

$$\overline{\overline{J}}_c(t) = 166.2\rho^{-1.98}, \tag{6}$$

with the mean square deviation $S_r = 0.052$ MPa^{-1} ($n = 18$) and determination coefficient $\eta^2_{J_c \cdot t} = 0.92$, showing that the ranging of $\overline{\overline{J}}_c(t)$ value depends by 92 % on the expanded polystyrene density and only by 8 % on other factors.

The average values of the creep strain of expanded polystyrene with given density and fixed compressive load $\sigma_c = 0.35\sigma_{10\%}$, for the period of time 10 years, can be calculated from empiric equations (6) and formula (2):

$$\bar{\varepsilon}_c(t = 10) = \overline{\overline{J}}_c(t)\sigma_c = 166.2\rho^{-1.98}\sigma_c. \tag{7}$$

It was determined that it is possible to evaluate the predicted average value of creep compliance or creep strains for any other time interval of $2 < t_i \le 50$ years according to the empiric equations (6) and (7) upon introduction of the enlargement factor $\overline{m}_{\bar{J}_c(t_i)}$. Their value may be approximated by the following regression equation:

$$\overline{m}_{\bar{J}_c(t_i)} = 0.55t^{0.26}, \tag{8}$$

with the mean square deviation $S_r = 0.059$ ($n = 90$) and determination coefficient $\eta^2_{J_c \cdot t} = 0.93$, were t is time in years.

Based on regression equations (6) – (8), for predicting the average creep strains of an expanded polystyrene with given density and fixed compressive load $\sigma_c = 0.35\sigma_{10\%}$, for any moment of time $t \le 50$ years, we can write the formula:

$$\bar{\varepsilon}_c(t \le 50) = 166.2\rho^{-1.98}\sigma_c \overline{m}_{\bar{J}_c(t_i)}. \tag{9}$$

Figure 6 presents prediction of the average values $\bar{\varepsilon}_c(t \le 50)$ of expanded polystyrene slabs, calculated according to the equation (9). Mean values of density for different EPS types calculated in accordance with [14] are indicated on an abscissa axis.

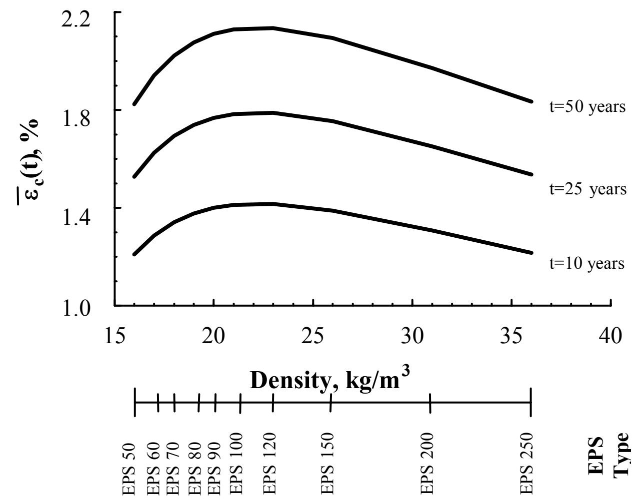


Fig. 6. The dependences of predicted values of average creep strains $\bar{\varepsilon}_c(t \le 50)$ for expanded polystyrene (EPS) slabs on the density under a fixed compressive stress $\sigma_c = 0.35\sigma_{10\%}$ for the different time period

CONCLUSIONS

1. The dependence of the creep compliance of expanded polystyrene (EPS) on density at fixed compressive stress $\sigma_c = 0.35\sigma_{10\%}$ was determined. Provided the values of creep compliance $\bar{J}_c(t)$ are known, it is possible to calculate the predicted creep strains of expanded polystyrene slabs exposed to fixed compressive stress $\sigma_c = 0.35\sigma_{10\%}$, for any period of time until 50 years.
2. The predicted values of $\overline{m}_{\bar{J}_c(t_i)}$, indicating increase ratio of creep deformation of EPS boards in long-term deformation, are expressed as the regression equation (8).
3. It was determined that the predicted values of creep strains of EPS60−EPS250 slabs for 50 years will not exceed 2.2 %, provided the slabs are exposed to compressive stress not greater than $0.35\sigma_{10\%}$.

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