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Article

Physical Properties of Foamed Concrete with the Addition of Polystyrene Granulate

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Abstract: According to EU Directives, it is necessary to improve the energy consumption of buildings. Therefore, the aim of this article is to improve the physical properties of foamed concrete produced on the basis of light plaster mortar. For this purpose, polystyrene granulate with a bulk density of 13 kg/m³ in the amount of 4, 7 and 10 g of 1 kg of light plaster mortar and a foaming agent in the amount of 2, 4 and 6% of the cement mass were used. Density, thermal conductivity coefficient and mechanical properties (compressive strength and tensile strength in bending) were determined. It can be observed that with the increase in the content of addition of polystyrene granulate, density, thermal conductivity coefficient and sorptivity were decreased, what is a positive phenomenon. However, at the same time, a reduction in mechanical properties was demonstrated. With the increase in the content of addition of foaming agent, density, thermal (except 2% of the foaming agent content) and mechanical properties were decreased. While sorptivity of all samples is lower than the basic sample, but sorptivity increases with the addition of a foaming agent for samples of samples with the addition of polystyrene granulate.

Keywords: foamed concrete; lightweight cellular concrete; pore material; synthetic foaming agent; pre-pared foam; air-void structure; compressive strength; thermal conductivity; multiple regression

1. Introduction

In accordance with EU Directives, there is a need to improve the energy efficiency of buildings. In the process of improving energy efficiency in construction, appropriate technologies and materials are used [1,2]. One way is to reduce heat transfer through horizontal and vertical partitions. Porous materials have lower heat transfer coefficients than materials with a continuous structure. This is due to the closure of small portions of gas (air, carbon dioxide) in their volume. However, if the spaces containing gas are too large, convection will begin to occur in them, which will increase the heat transfer coefficient of a given building material. This is the basis for the use of foamed mortar in construction. However, the term foamed mortar is not widely used. The term foamed concrete is more often used, despite the fact that foamed concrete does not contain coarse aggregate, and often fine aggregate (sand). Foamed concrete (FC) is classified as lightweight concrete with density ranging from 280 to 1800 kg/m³ [3–5] and with a minimum of 20% of air-pores volume in the cementitious mix [6,7]. Due to the air pore structure of the cement matrix, foamed concrete is characterized by good properties thermal [8–13]. The thermal conductivity coefficient ranges from about 0.1 W/(m·K) to 0.7 W/(m·K) for foamed concrete with density ranging from 600 kg/m³ to 1600 kg/m³ [14–19]. For the appropriate composition of foamed concrete, a thermal conductivity coefficient of up to 0.048 W/(m·K) can be achieved at a density below 500 kg/m³ [20,21]. For example, Proshin et al. [22] used polystyrene granulate additives as composite of foamed concrete mix and they obtained a thermal conductivity coefficient in the range from 0.06 W/(m·K) to 0.16 W/(m·K) for foamed concrete with a density of 200 kg/m³ to 650 kg/m³.

However, these were single research results for given compositions of foamed concrete mixes. The physical properties of foamed concrete are closely related to the composition of the foamed concrete mix. The basic components of a foamed concrete mix are cement and a foaming agent of protein or synthetic origin. The remaining components are the same as in the case of other cement composites, i.e. water and possibly aggregate, whereby there is no coarse aggregate, and often also fine aggregate. In addition, various additions, including those from recycling, may be used. Therefore, this study aims to assess the physical properties of hardened foamed mortar with polystyrene granulate addition. Compared to previous studies [23,24], foamed concrete was produced on the basis of light plaster mortar. In addition, since tests of such foamed mortar have not been conducted so far, the its mechanical properties and sorptivity were also assessed as part of this study. Moreover, the sorptivity of foamed concrete/foamed mortar are very rarely found in the literature. The authors found only a few literature items presenting the results of such studies, e.g. [25–27]. However, this is particularly important due to the potential application of foamed concrete/foamed mortar.

2. Materials and Methods

2.1. Specimen Preparation

The materials used in this study were light plaster mortar in the loose state, tap water and foaming agent. A ready-made mortar, commercially available (SEMPRE Farby Sp. z o.o., Bielsko-Biała), was used. The composition of the light plaster mortar was presented in the Table 1.

Table 1. The composition of the light plaster mortar [28].

Composite	Quartz sand 0.0-0.5 mm	Cement CEM I 42.5 R ¹	Filling aggregate (limestone flour)	Lime	Expanded perlite	Redispersible polymer powder (polyvinyl acetate modified with ethylene)	Thickener (hydroxyethyl methyl cellulose with a viscosity of approx. 15,000 mPa·s)	Foaming agent based on alpha-olefin sulphate and sodium salt
Unit (vol. %)	63.02	20.00	10.00	5.00	1.20	0.50	0.25	0.03

In this study, a commercial liquid polymer admixture with specific gravity of 1.02 g/cm³ was used as synthetic foaming agent. The synthetic foaming agent (MEEX, Chrzanów, Poland) contents were 2.0, 4.0 and 6.0% of cement mass.

Moreover, an addition of polystyrene granulate with a bulk density of 13 kg/m³ was used (Figure 1).



¹ according to PN-EN 197-1:2011

Figure 1. Used polystyrene granulate addition (own photo).

2.2. Mix Composition

Specimens of foamed mortar with three different polystyrene granulate addition content were produced (see Table 2). The addition of polystyrene granules was 10, 7 and 4 g/1 kg of light plaster mortar, respectively. Polystyrene granulate (PG) content was selected so that bulk density of light plaster mortar and granulate were at the same (volume proportions 1:1), and the next amount of PG addition was decreased and increased.

Table 2. Mix proportions on 1 batch.

Mix symbol	Light plaster mortar [kg]	Polystyrene granulate addition [g]	Water [kg]	Foaming agent [% of cement mass]
Serie 13-1	12	120	3.120	0.0
	12	120	3.072	2.0
	12	120	3.024	4.0
	12	120	2.976	6.0
Serie 13-2	12	84	3.120	0.0
	12	84	3.072	2.0
	12	84	3.024	4.0
	12	84	2.976	6.0
Serie 13-3	12	48	3.120	0.0
	12	48	3.072	2.0
	12	48	3.024	4.0
	12	48	2.976	6.0

2.3. Mix Production

The foamed concrete mix were produced according to the pre-forming method. Firstly, water and light plaster mortar were mixed. After six minutes, the polystyrene granulate was added and all components were mixed by ~~two~~ one minute. Next, the stable foam was added and all components were mixed (Figure 2a). The foam is created using a foam generator. The key factors in producing stable foamed concrete included the pressurising of the foaming agent at stable pressure and mixing the components in constant rotational speed [24].

All specimens were cast in steel moulds (Figure 2b,c) and were covered with cellophane to protect against water evaporation and to ensure the best bonding conditions [29] in a curing room at 20±1°C for 24 hours. Subsequently, the samples were removed from the moulds and stored in a curing room at 20±1°C and 95% humidity for 14 days. After this time, foamed concrete samples were stored in ambient conditions (at 20±1°C and 60±10% humidity). After 28 days of curing, hardened mortar were tested. Two cases were considered, in the first a mortar with the addition of polystyrene granulate, and in the second a foamed mortar with the addition of polystyrene granulate. The results were compared with the base sample (mortar without the addition of polystyrene granulate and foaming agent).



Figure 2. Samples production process a) mix of light plaster mortar with polystyrene granulate addition, b) adding foam to light plaster mortar with polystyrene granulate addition, c) foamed mortar mix, d) samples with foamed mortar in steel moulds (own photos).

2.4. Methodology

2.4.1. Density

The density of specimen of foamed mortar was measured with 150×150×150 mm standard cubes as per PN-EN 1015-10 [30]. Three naturally dried samples for each mix were examined.

2.4.2. Thermal Conductivity

Thermal conductivity was measured on samples 150×150×50 mm (Figure 3). This device operates based on the relative method of measuring the λ coefficient, which consists in measuring the ratio of the thermal resistance of the tested samples to the resistance of the reference samples. The measurement is performed at a constant average sample temperature and a constant temperature difference on the upper and lower surfaces of the sample and at a constant and uniform heat flux crossing the sample measurement area. Three samples per each mix were tested. The samples were dried to a constant mass before testing.

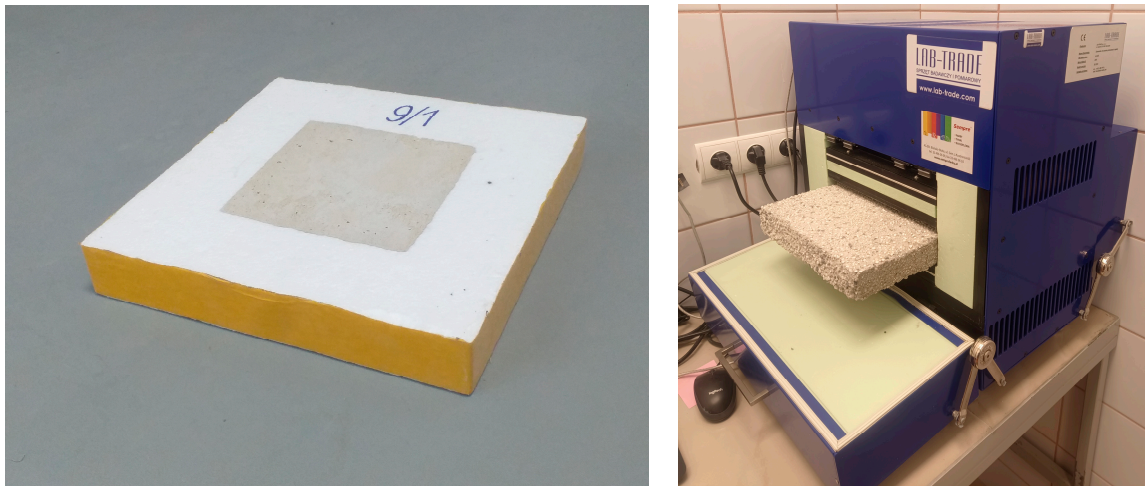


Figure 3. Foamed concrete samples prepared for testing the thermal conductivity coefficient (own photos).

2.4.3. Flexural Strength

Flexural strength was determined in the three-point bending test of beams with dimensions of 40×40×160 mm (Figure 4a) in accordance with the PN-EN 1015-11 [31]. Three naturally dried samples per each mix were tested.

2.4.4. Compressive Strength

The compressive strength was determined on the beam halves obtained after the flexural strength test (Figure 4b) in accordance with the PN-EN 1015-11 [31].

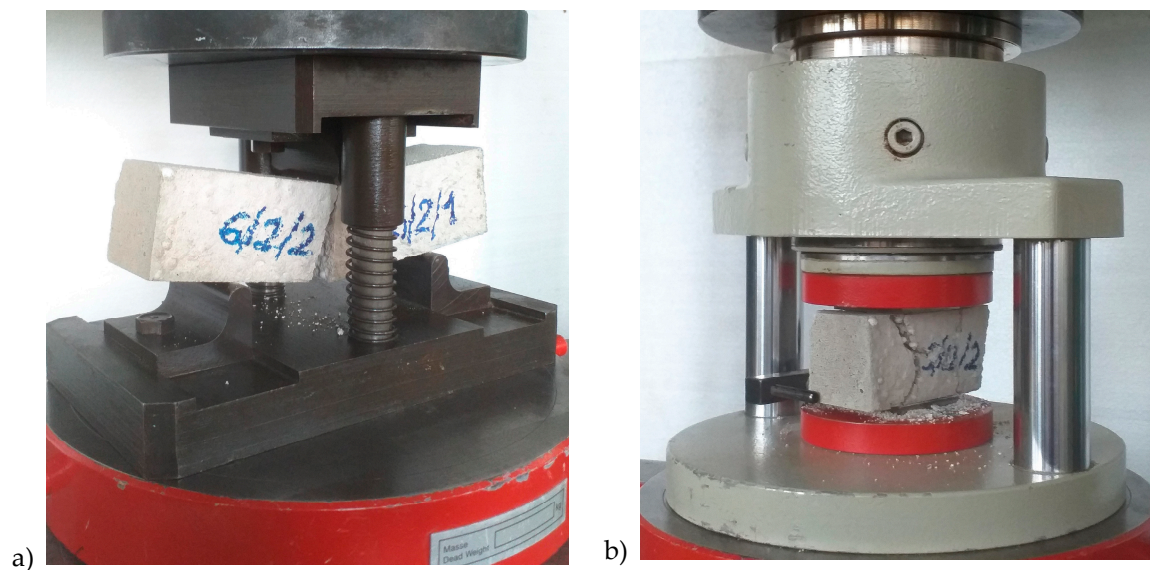


Figure 4. Test of mechanical properties of foamed mortar: a) flexural strength, b) compressive strength (own photos).

2.4.5. Sorptivity

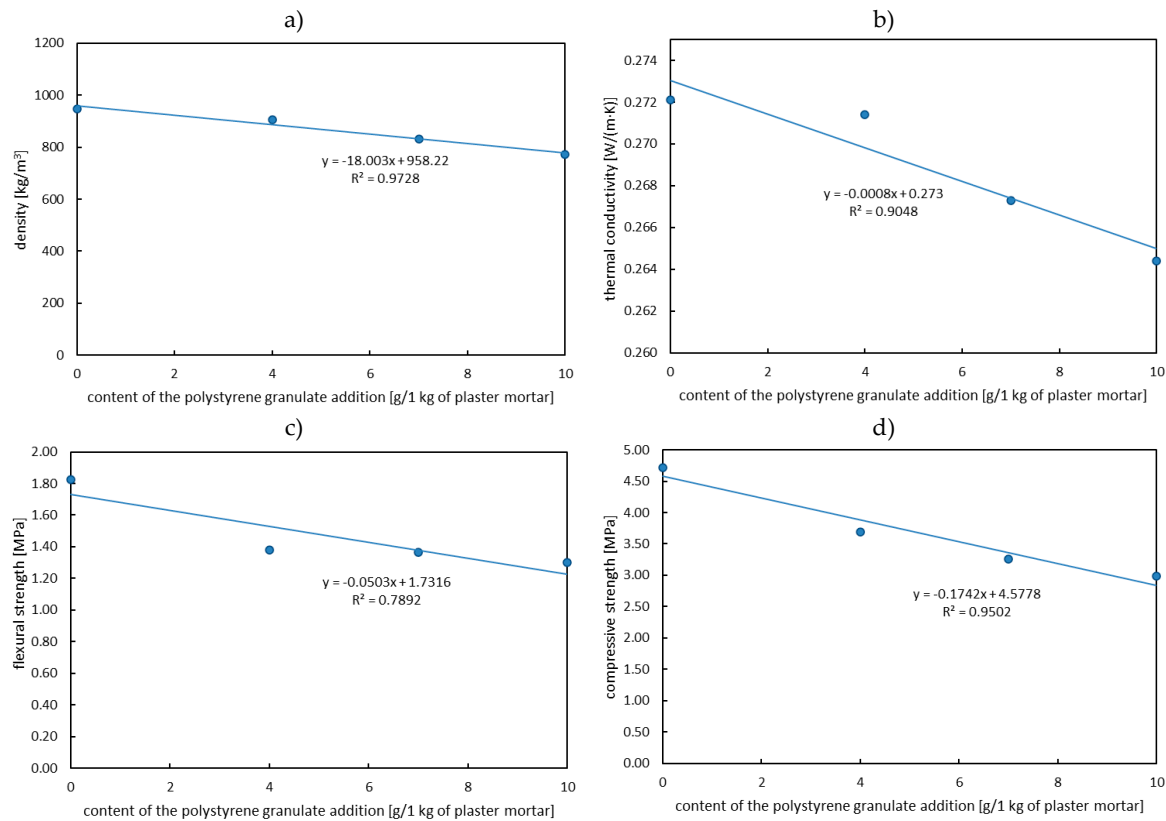
The sorptivity was measured on samples 40×40×160 mm (Figure 5) as for ordinary (non-renovation) mortars according to PN-EN 1015-18 [32].



Figure 5. Sorptivity test of foamed mortar (own photo).

3. Results and Discussion

In the first case, the effect of the addition of polystyrene granulate on the mortar properties (without the addition of a foaming agent) was analyzed. It can be seen that with the increase in the content of addition of polystyrene granulate, density (Figure 6a), thermal conductivity coefficient (Figure 6b) and sorptivity (Figure 6e) were decreased, what is a positive phenomenon. However, at the same time, a reduction in mechanical properties was demonstrated (Figure 6c,d). The largest decrease in values compared to base sample was obtained for sorptivity and mechanical properties (flexural and compressive strength), see Table 3.



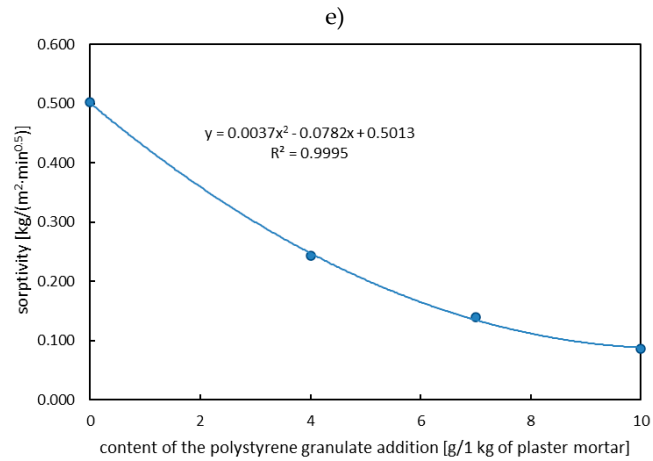
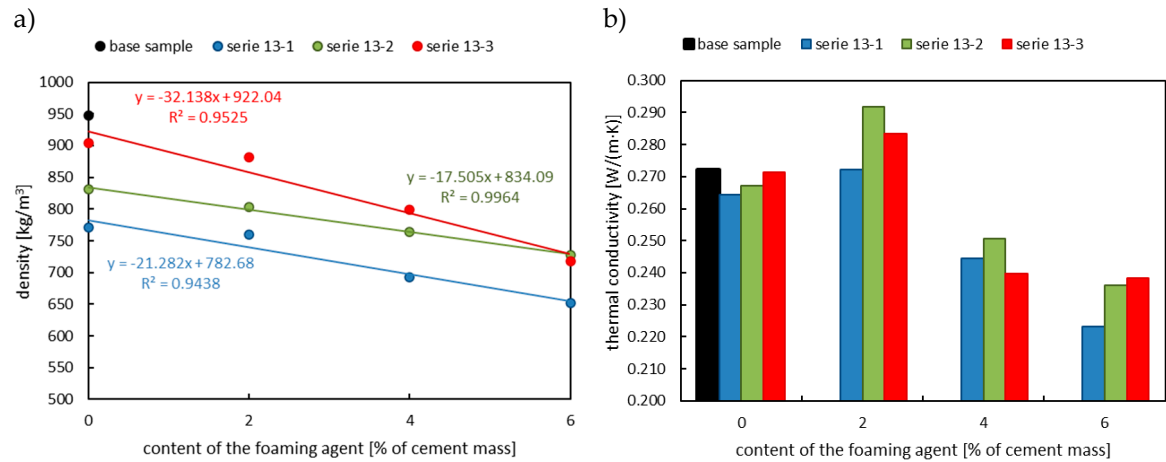


Figure 6. The effect of polystyrene granulate addition on the physical properties of base mortar.

Table 3. Percental decrease in physical properties of light plaster mortar with polystyrene granulate addition compare to base light plaster mortar.

No.	Decrease in [%]				
	density [kg/m³]	λ [W/(m·K)]	f _{tk} [MPa]	f _c [MPa]	sorptivity [kg/(m²·min ^{0.5})]
Serie 13-1	18.6	2.8	28.8	36.8	82.8
Serie 13-2	12.2	1.8	25.4	31.1	72.2
Serie 13-3	4.5	0.3	24.5	21.7	51.6

In the second case, the impact of the foaming agent content on the properties of the plaster mortar with different content of polystyrene granulate was analyzed. It can be seen that the effect of the foaming agent content on the analyzed physical properties of the foamed mortar with the addition of polystyrene granulate is not unambiguous, see Figure 7.



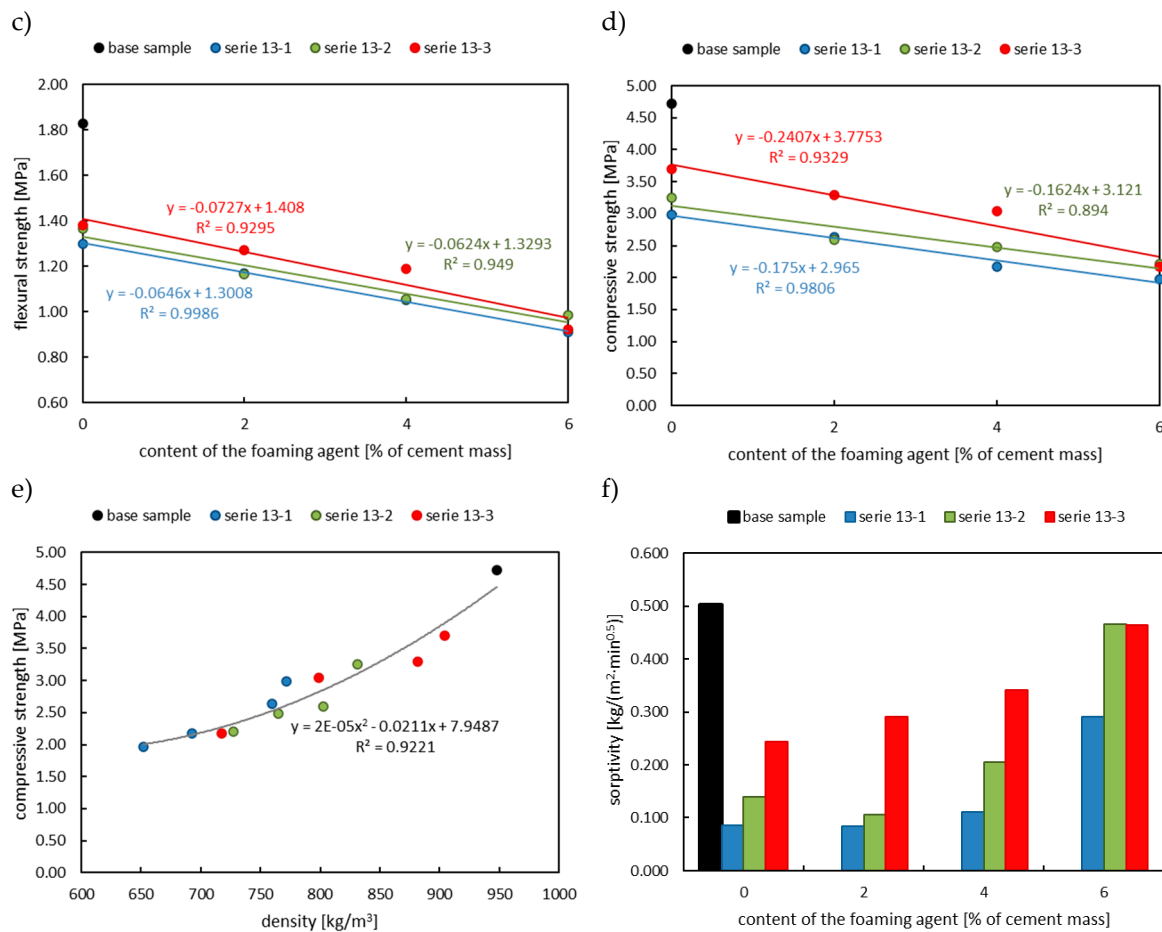


Figure 7. The effect of polystyrene granulate addition on the physical properties of foamed mortar

Figure 7a presents the results of average densities of the hardened foamed mortar with addition of polystyrene granulate for foaming agent content of 2.0, 4.0 and 6.0% of cement mass. It can be observed that the density of foamed mortar decreased with increasing foaming agent content and this correlation is linear. The volume of foam commonly created air voids and resulted in lower density [25]. These results are consistent with the observations for foamed concrete of the basic composition [6,7,23,24]. The situation is different in the case of other properties of foamed concrete. Usually, a decrease in the mechanical properties and in the thermal conductivity coefficient of foamed concrete is observed with a decrease in density, which is proportional to the increase in the foaming agent content [3,25]. In the analyzed case, the lowest thermal conductivity coefficient of foamed mortar was obtained for the highest foaming agent content, regardless of the content of polystyrene granulate. However, with a foaming agent content of 2% of the cement mass, this value was higher compared to the base sample of plaster mortar and base samples of plaster mortar with addition of polystyrene granulate, see Figure 7b and compare to Figure 6b.

Mechanical properties are directly related with density and at the same foaming agent content [14,23–25], while with decrease in foaming agent content (increase in density), flexural and compressive strength also increased [3,25]. It is related with the fact, that the addition of foaming agent decreased strength because the volume of foam created pores resulting in lower density [24]. The obtained results showed that the flexural (Figure 7c) and compressive strength (Figure 7d) of foamed mortar was halved with a foaming agent content of 6% of cement mass compared to the base mortar. Figure 7e presents the correlation between density and compressive strength for foamed mortar with different foaming agent content and polystyrene granulate addition. It can be seen that this correlation is exponential, which is consistent with the results of own [24,33] and other researchers [25,29,34–37] for other foamed concrete mixture compositions. It should be noted the high

agreement of the correlation equation obtained in this study and in previous research results for foamed concrete with the basic composition [22,24,33].

Moreover, an interesting observation is that sorption is lower with a higher content of foaming agent, regardless of the content of polystyrene granulate, see Figure 7f. The lowest values were obtained for polystyrene granulate with the highest content analyzed. There are no results for comparison in the literature, therefore research in this area will be conducted for other compositions of foamed concrete mixes.

In order to determine the quantitative relationship between the change in the amount of the addition of polystyrene granulate (X1) and foaming agent (X2), and the compressive strength and bending strength, thermal conductivity coefficient, density and sorptivity of hardened foamed concrete, multiple regression was used. A linear model was used according to (1).

$$Y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + \dots + b_k \cdot X_k + \varepsilon, \tag{1}$$

where:

b_i – model parameter (regression coefficient) describing the impact of the i -th variable,
 ε – random component (standard error of the estimation Se).

The verification of the models was carried out by assessing the significance of the regression function, regression coefficients and based on the analysis of residuals. The significance of the models was tested with the F test at the probability level of $p=0.05$. The multiple correlation coefficient R and the R^2 index, which determines how much of the variability of the dependent variable is explained by the remaining variables, were adopted as a measure of interdependence between one of the variables and the other variables treated together. Table 4 presents the results of multiple regression.

Table 4. Multiple regression results.

Dependent variable	$F(2,9)$	p	Se	R	R^2
Thermal conductivity coefficient [W/(m·K)]	8.8252	<0.0076	0.01544	0.81381	0.58248
Density [kg/m ³]	60.383	<0.0001	21.565	0.96469	0.91523
Flexural strength [MPa]	85.29	<0.0000	0.04034	0.97461	0.93874
Compressive strength [MPa]	20.601	<0.0004	0.24348	0.90593	0.78088
Sorptivity [kg/(m ² ·min ^{0.5})]	0.9052	<0.0004	0.06505	0.90521	0.77924

In each case, the F -values are greater than the critical values of the F – Snedecor distribution at a significance level of 0.05 ($F(2,6)_{cr} = 4.26$). The significance of the models is also confirmed by the determined p -values, which are less than the generally accepted value of 0.05. The correlation coefficients $R \approx 1$ mean that there is a strong linear relationship between the variables. In the next step, the significance of the regression coefficients was assessed, see Table 5.

Table 5. Regression results.

Dependent variable	b_0	p -value	b_1	p -value	b_2	p -value
Thermal conductivity coefficient [W/(m·K)]	0.2829	0.000	-0,00041	0,818	-0.0084	0,002
Density [kg/m ³]	970.875	0.000	-17.7917	0.005	-23.583	0.000
Flexural strength [MPa]	1.44192	0.000	-0.01375	0.017	-0.0663	0.000
Compressive strength [MPa]	3.97241	0.000	-0.10291	0.005	-0.1673	0.000
Sorptivity [kg/(m ² ·min ^{0.5})]	0.33815	0.000	-0.03204	0.002	0.0406	0.000

It can be observed that in the case of testing the variation of density, compressive and flexural strength and sorptivity, the p -values for partial regression coefficients are significant ($p < 0.05$).

In the case of testing the variation of the thermal conductivity coefficient λ , the independent variable - the content of the addition of polystyrene granulate X_1 [%] - is insignificant. The independent variable X_2 - the content of the foaming agent - is highly significant. However, it was observed that the variation of the dependent variable was explained by 58% ($R_{corrected} = 0.58724843$).

Such a model may be acceptable in complex systems, in which other factors may have an influence. For the λ coefficient, a well-fitting model was obtained in the form of formula (2).

$$\lambda = 0.282919 - 0,008423 \cdot X_2 \pm 0.01544, \tag{2}$$

In the next step, the redundancy (lack of collinearity) between independent variables was determined. For each variable, the R^2 coefficient, tolerance, partial and semi-partial correlations were calculated. The semi-partial correlation (also called partial correlation) describes the relationship between two variables, while controlling for the impact of one or more additional variables. In order to illustrate trends and graphically represent the structure of the data, surface plots were made, see Figures 8–11. Figure 8 present the variation of the thermal conductivity coefficient λ and the results of the redundancy test. Analyzing the results, it was found that the semi-molecular correlation for the variable X1 (content of the addition of polystyrene granulate) was very small and amounted to -0.02. This indicates a weak correlation of this variable with the dependent variable λ . On the other hand, the variable X2 (content of the foaming agent) is highly correlated and explains 82% of the variation of the coefficient λ .

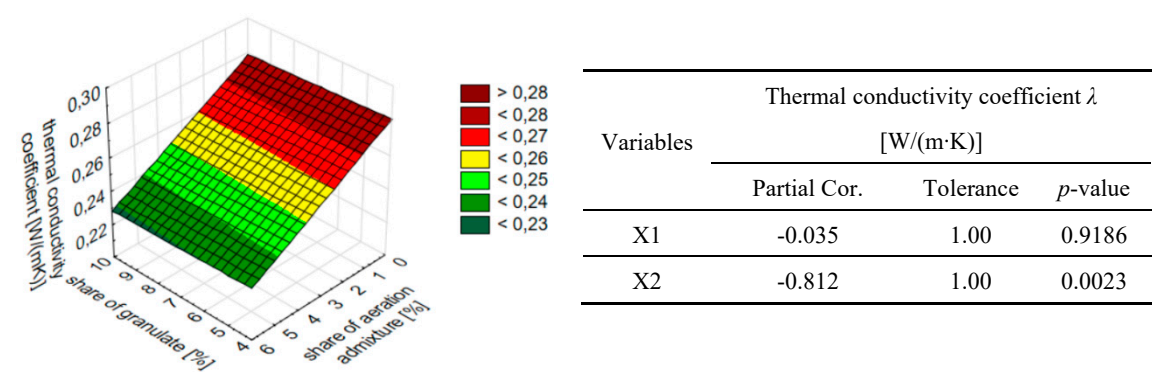


Figure 8. The effect of the simultaneous addition of polystyrene granulate X1 [%] and foaming agent X2 [%] on the thermal conductivity coefficient of foamed concrete λ [W/(m·K)] described by a linear model.

A high semi-molecular correlation of both independent variables (X1 and X2) was observed for the density, compressive and flexural strength as well as sorption of foamed concrete.

The trends in the changes in the density of foamed concrete are presented in Figure 9. The semi-partial correlations between the independent variables and the density are comparable and amount to -0.943 for the foaming agent content (X2) and -0.919 for the content of polystyrene granulate addition (X1). This means that the changes in the content of these components affect the change in the density of foamed concrete to a comparable extent (the strength of the interaction of both variables is comparable, but the variables are inversely correlated).

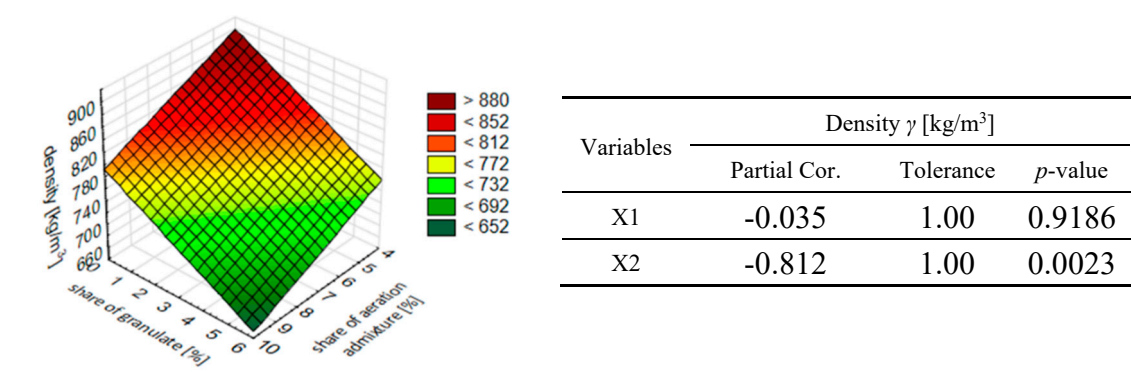


Figure 9. The effect of the simultaneous addition of polystyrene granulate X1 [%] and foaming agent X2 [%] on the density of foamed concrete γ [kg/m³] described by a linear model.

Figure 10 presents a surface graph of the variation of compressive strength of hardened foamed concrete. During the redundancy test, it was found that the semi-partial correlations between the independent variables and density are diverse and amount to -0.871 for the foaming agent content (X2), and -0.767 for the polystyrene granulate addition content (X1). This means that the effect of the change in the amount of the foaming agent on the change in the compressive strength of foamed concrete is greater (the strength of the effect of this variable is greater than the change in the content of the polystyrene granulate additive). However, the variables are inversely correlated.

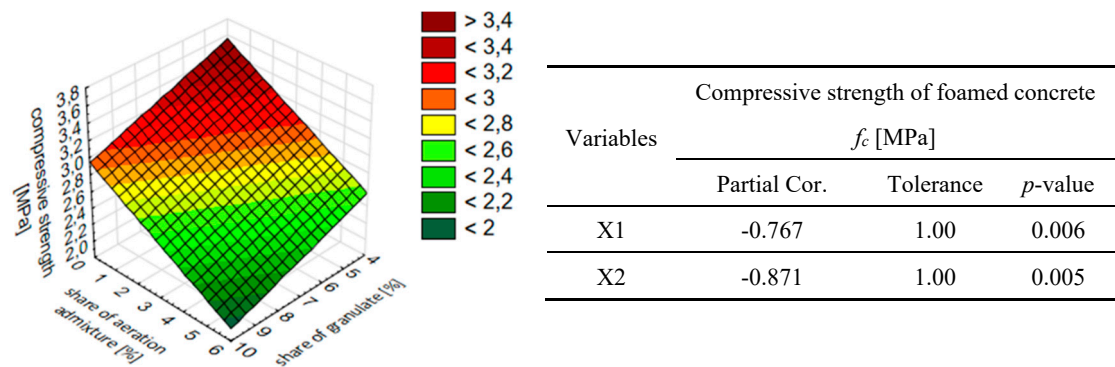


Figure 10. The effect of the simultaneous addition of polystyrene granulate X1 [%] and foaming agent X2 [%] on the compressive strength of foamed concrete f_c [MPa] described by a linear model.

For the study of the flexural strength variation, a strong correlation was shown with the change in the foaming agent content (X2) - level 95%. The impact of the polystyrene granulate addition content is insignificant, see Figure 11. The trends of the simultaneous influence of the change in the amount of the foaming agent X2 and the addition of polystyrene granulate X1 on sorptivity are presented in Figure 12.

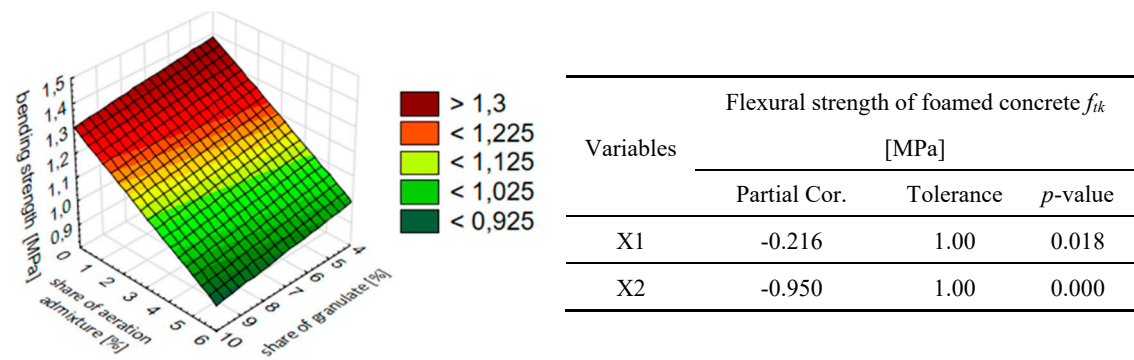


Figure 11. The effect of the simultaneous addition of polystyrene granulate X1 [%] and foaming agent X2 [%] on the flexural strength of foamed concrete f_{tk} [MPa] described by a linear model.

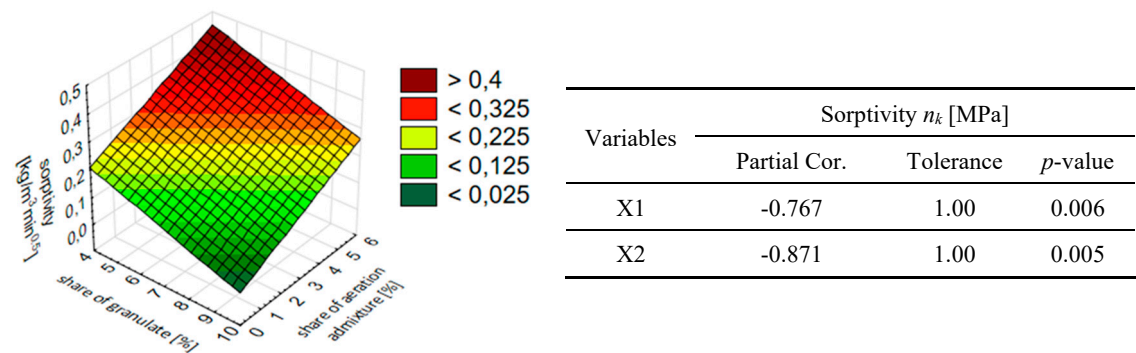


Figure 12. The effect of the simultaneous addition of polystyrene granulate X1 [%] and foaming agent X2 [%] on the sorptivity n_k [MPa] described by a linear model.

Analyzing the partial correlations, it can be stated that both variables are similarly correlated. This means a strong relationship between both independent variables X1 and X2 with sorptivity. Wherein the variable content of the foaming agent is inversely correlated.

5. Conclusions

The aim of the study was to assess the physical properties of hardened foamed mortar with polystyrene granulate addition. In this study foamed concrete was produced on the basis of light plaster mortar. The polystyrene granulate with a bulk density of 13 kg/m³ in the amount of 4, 7 and 10 g of 1 kg of light plaster mortar and a foaming agent in the amount of 2, 4 and 6% of the cement mass were used. Based on the results of this experimental investigation, the following key conclusions can be drawn:

- With the increase in the content of addition of polystyrene granulate, density, thermal conductivity coefficient and sorptivity were decreased, what is a positive phenomenon. However, at the same time, a reduction in mechanical properties was demonstrated.
- Sorptivity of all samples is lower than the base sample of light plaster mortar, but sorptivity increases with the addition of a foaming agent for samples with the addition of polystyrene granulate.
- The addition of polystyrene granulate affects the density of foamed mortar in a similar way to a foaming agent. Both components can be used to regulate the density of this product.
- The addition of polystyrene granulate reduces the flexural strength to a lesser extent than the foaming agent. Also in the case of compressive strength, a greater decrease was noted for samples with an increased amount of foaming agent.
- The addition of polystyrene granulate reduces the sorption of foamed mortar, while the addition of a foaming agent increases it.
- The effect of polystyrene granulate on the thermal conductivity coefficient is insignificant. Hence, the addition of granulate is not an equivalent of a foaming agent, but can be an interesting addition to the composition of foamed concrete mix, foamed slurry or foamed mortar.

Based on the conducted research, it can be concluded that in the analyzed foamed concrete formulation, polystyrene granulate combined with a foaming admixture provides new possibilities in modeling the physical properties of foamed building materials. However, in order to determine the exact impact on individual values, further research is planned in this area.

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