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INFLUENCE OF DIFFERENT LOADS ON THE PROPERTIES OF LIGHTWEIGHT COMPOSITE

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Abstract. The paper describes the study on the operational properties of lightweight composite with density of 150–350 kg/m^3. It was established that these properties depend on the ratio of porous cement matrix and inclusions of crushed expanded polystyrene packing tare waste per unit volume of the lightweight composite. Studies have demonstrated that when the density of lightweight composite varies in the above mentioned limits, the compressibility amounts to 2.4–0.8 mm, point load – 0.38–3.39 kN, dynamic stiffness – 35–135 MN/m^3, and reduction in normalised impact sound pressure level – 26–17 dB. The dependences between the established properties and the density of lightweight composite are showed in the equations of regression. Possible versions for the use of lightweight composite in different constructions of floors and roofs are also provided.

Keywords: expanded polystyrene waste, compressibility, point load, dynamic stiffness, normalised impact sound pressure level.

1. Introduction

Plastics play an important role in our lives. They have been used in housing, packing, preservation and distribution of goods, many automotive, industrial and healthcare applications (Siddique *et al.* 2008). The rapid growth in the use of plastics leads in increased total garbage volume in dumps, causing serious environmental problems (Vasudevan *et al.* 2012).

It is possible to reduce the amount of plastic waste in dumps by using it as a raw material in the composites for the applications in civil engineering (Leu *et al.* 2012; Ahmed *et al.* 2011; Binici *et al.* 2012; Mohandesi *et al.* 2011). Utilisation of plastic waste saves manufacturing costs, CO_2 emissions and natural raw materials (Poletto *et al.* 2011).

Expanded polystyrene (EPS) is a type of plastic, known for being hygienic and lightweight, highly able to absorb shocks, inexpensive, dimensionally stable and easy to produce (Shin 2006; GHK 2010; Schmidt *et al.* 2011). All these qualities make them irreplaceable for production of packing tare. Vast amounts of EPS packing tare are used for electronic devices, apparatus and their parts to ensure their safe transportation from manufacturer to customer.

Spherical EPS inclusions are also widely used to produce lightweight cement-based composites (Madandoust *et al.* 2011; Xu *et al.* 2012; Bouvard *et al.* 2007; Guan *et al.* 2007). These composites have lower density, better thermal insulation and energy absorption.

In natural conditions, EPS waste does not disintegrate for very long periods of time, and its pressing is difficult because of reversible deformation (Kligys 2009). Some authors (Bhutta *et al.* 2011; Poletto *et al.* 2011; Schmidt *et al.* 2011; Gaggino 2006) have proposed innovative technologies for recycling of EPS waste by introducing them into the manufacturing process of different composites.

Quite recently the utilisation of EPS packing tare waste was a serious problem in Lithuania as it was simply dumped. Only as late as in 2006, the private company Virginijus and Co., Plungė, Lithuania developed a technology for the Eureka project E! 3446-Sandplast. Now, this company crushes EPS packing tare waste to required dimensions and uses it as an inclusion for the production of lightweight composite, offered by the VGTU Scientific Institute of Thermal Insulation. In this lightweight composite – with a density from 150 to 350 kg/m^3 – EPS inclusions are joined by a porous cement matrix.

The earlier researches (Sinica *et al.* 2008; Kligys *et al.* 2008) showed that the limit compressive strength σ_c of lightweight composite makes 0.09–0.42 MPa, the limit flexural strength σ_b is 0.09–0.39 MPa, the thermal conductivity coefficient $\lambda_{10^\circ C}$ is 0.0489–0.0963 W/m·K, the specific water vapour resistance μ is 6.0–14.8. According to the standard LST EN 13501-1:2007, by class of combustibility, the lightweight composite may be allocated to class B-sl, d0.

Nevertheless, these properties are not enough to possibly extend the field of application of this lightweight composite, e.g. for floating floor or roof insulating constructions, where during the process of exploitation, different loads appear. Therefore, it is necessary to carry out the additional research of lightweight composite to determine such properties, as compressibility, ability to stand static and dynamic loads, as well as normalised impact sound pressure level.

Presently, in constructions of floating floor and flat roofs, lightweight materials, e.g. mineral wool and expanded polystyrene slabs are widely used. The operational properties of such materials is well investigated; therefore, it is of no difficulty to select any special material for different constructions (Buska *et al.* 2008; Dikavičius, Miškinis 2009; Miškinis 2010; Kim *et al.* 2009). However, the analysis of references showed that no sufficient data are available on abovementioned properties of lightweight composite. The purpose of this study is to investigate these properties.

2. Materials and methods

2.1. Materials and preparation of samples

Lightweight composite was produced using Portland cement of mark CEM I 42.5 R conforming to requirements of the standard LST EN 197-1:2000, manufactured by the Joint Stock Company Akmenės Cementas, Naujoji Akmenė, Lithuania. The setting time of Portland cement is determined by the standard LST EN 196-3:2005+ A1:2009: t_n – 140 min, t_k – 190 min. The chemical composition (in %) is determined by the standard LST EN 196-2:2005: SiO_2 – 20.76; Al_2O_3 – 6.12; Fe_2O_3 – 3.37; CaO – 63.50, MgO – 4.01; (K_2O + Na_2O) – 1.03; SO_3 – 0.80; burning loss – 0.23, insoluble residue – 0.07. The mineral composition of Portland cement (%), calculated by the method (Bogue 1955), was the following: C_3S – 58.54; C_2S – 15.29; C_3A – 10.40; C_4AF – 10.17. The specific surface of Portland cement, determined by Blein device according to the standard LST EN 196-6:2010 was 420 m^2/kg.

EPS inclusions were received by crushing EPS packing tare waste at the Joint Stock Company Virginijus and Co., Plungė, Lithuania. The bulk density of EPS inclusions (13–17 kg/m^3) was determined according to the standard LST EN 1097-6+AC:2003/A1:2005. The particle size distribution (presented in Table 1) was determined according to the standard LST ISO 3310-1:2003/AC1:2005, using the set of sieves conforming to the standard LST EN 933-1:2002.

As a foamer, the air entraining additive (AEA) Ufapore TCO, Unger Fabrikker AS, Fredrikstad, Norway, was used in amount of 0.03% of Portland cement mass.

The compositions of formative mixtures of lightweight composite, subject to its density, are presented in Table 2.

The components of formative mixture were mixed by a vertical mixer MXP 1602 E, Protool, Česká Lípa, Czech Republic at a speed of 125 rpm observing the following procedure and the duration of mixing. Water and AEA were mixed for 1 minute, then Portland cement was added and the mixing was continued for additional 2 min, afterwards, EPS inclusions in required amount were added to porous cement mixture and mixed further for 5 min to uniform mass.

The prepared formative mixture was poured into moulds of required dimensions. To fill the moulds evenly, the formative mixture was slightly compacted by a metal rod of 20 mm diameter.

The obtained specimens of lightweight composite were demoulded after 24 hours since moulding, and then – covered with polyethylene film and kept for 28 days at a temperature of 20 °C. Finally, they were dried in the laboratory drying oven at a temperature of 50 °C to a constant mass.

2.2. Testing methods

The density in a dry condition of lightweight composite was determined on specimens of cube shape (100×100×100) mm by the standard LST EN 1602+ AC:1998.

For determination of compressibility and point load of lightweight composite, the electromechanical testing machine H10KS, Hounsfield Test Equipment LTD, Redhill, England, was used with the computer program

Table 1. Particle size distribution of EPS inclusions

Value of mesh cell (mm)	20.00	10.00	5.00	2.50	1.25	<1.25
Fractional residue (%)	0.37	20.02	29.79	22.99	25.48	1.35
Full residue (%)	0.37	20.39	50.18	73.17	98.65	100
Aperture (%)	99.63	79.61	49.82	26.83	97.30	0.00

Table 2. Compositions of formative mixtures of lightweight composite with different densities

Density of composite, kg/m^3	Size of EPS crumbs (mm)	Portland cement and EPS crumbs ratio (mass %)	Water and Portland cement ratio
150	Not more than 5.00	83:17	0.80
250	Less than 20.0	91:9	0.65
350	Less than 20.0	94:6	0.50

Qmat Professional. The compressibility was determined according to requirements of the standard LST EN 12431:2000/A1:2007, upon exposure to testing of 10 specimens sized (200×200×50) mm for each series of density, the combination of static loads being presented in Fig. 1. The compressibility value of lightweight composite was measured as a difference between thicknesses d_L and d_B (Fig. 1).

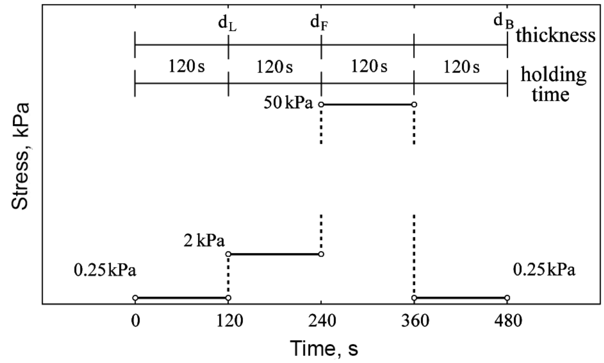

Fig. 1. Scheme of variation of thickness of lightweight composite depending on time and load

The static point load was determined on 10 specimens sized (300×300×50) mm according to the standard LST EN 12430:2000/A1:2007, by fixing value of static compressive force at the critical point in the force-deformation curve of lightweight composite (Fig. 2). The indentor was set to move at a constant speed of 50 mm/min. The deviation of force measurement was 1–11 N. The precision of deformation in specimens of lightweight composite (according to motion of traverse) was 0.01 mm. The testing ran at ambient temperature of 23±2 °C and relative air humidity of 50±5%.

The dynamic stiffness was determined according to the standard LST EN 29052-1:2002 by measuring of resonance frequency with the system DYPS3, Ing. Wolfgang Fellner GmbH, Vienna, Austria. 10 specimens sized (200×200×50) mm were tested for each density of lightweight composite.

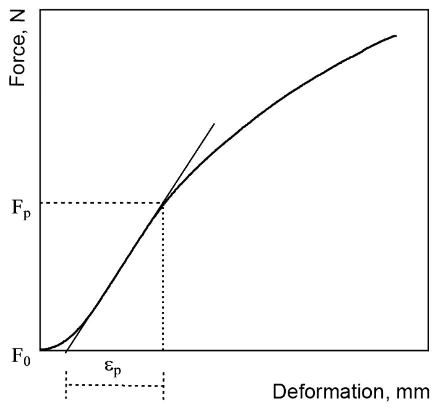

Fig. 2. Example of force-deformation curve of lightweight composite: F_p – compressive force at critical point; F_0 – force corresponding to the preload; ε_p – deformation at F_p

The reduction in normalised impact sound pressure level was determined according to the methodology (Pavoni Belli *et al.* 2003) by simplified formula:

$$\Delta L_w = 18 + 15 \cdot \log \frac{m}{s}, \tag{1}$$

where: ΔL_w – decrease in normalised impact sound pressure level in dB; m = 110 kg/m^2 is a load of floating floor; s – dynamic stiffness in N/m^3.

The statistical processing and interrelation between two variables of experimental data was performed according to the program Satistica by least squares method (Sakalauskas 1998; Lakin 1990). The best approximating relationship was selected from some relationships via comparison of mixed correlation coefficient $R^2_{y.x}$ (squared correlation relationship $R_{y.x}$). The mean square deviation S_r was admitted as a result scattering measure.

The surface morphology of lightweight composite was determined by stereomicroscope K-400L, Motic Group Co. LTD, Xiamen, China, with magnification up to 100× equipped with digital imagining system PVC 100C, Pixera Corporation, Los Gatos, USA.

3. Results and discussion

3.1. Compressibility

The results of investigations showed that the compressibility of lightweight composite decreases along with an increase in its density. Thus, for the lightweight composite of 150 kg/m^3 density, the compressibility under impact of given standard loads made 2.41–2.62 mm; for 250 kg/m^3 density, it was 1.53–1.69 mm and for 350 kg/m^3 density – 0.63–0.81 mm, i.e., the compressibility of lightweight composite can be characterised by amount and porosity degree of the matrix. Thicker walls composed of porous matrix can hinder the impact of force loads and thereby they help protecting EPS inclusions from possible deformations. The relationship between compressibility c and density of lightweight composite ρ_a can be expressed by the following equation of regression (Fig. 3):

$$c = 3.86 - 0.00902 \cdot \rho_a, \tag{2}$$

with the mean square deviation S_r = 0.055 mm (n = 30) and coefficient of determination $R^2_{c \cdot \rho_a}$ = 0.994, showing that the variation of compressibility of lightweight composite is by 99.4% preconditioned by change in its density.

The data presented in Fig. 3 show that at density of lightweight composite as high as 250 kg/m^3, the mean value of compressibility (1.63 mm) is lower by 34.3% than the analogical parameter at 150 kg/m^3 density (2.48 mm). At 350 kg/m^3 density of lightweight composite, this value decreases by 54.4% (down to 0.71 mm) versus 250 kg/m^3 density and by 71.4% versus 150 kg/m^3 density.

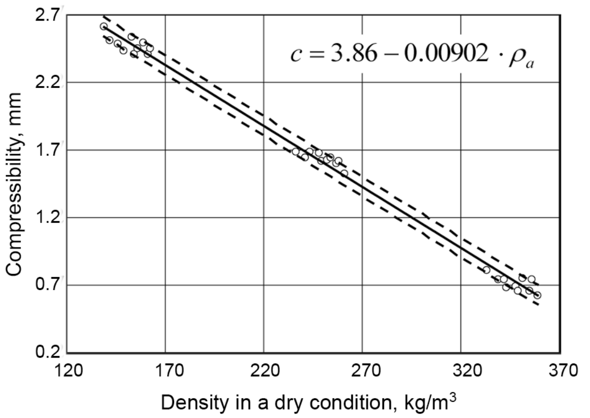

Fig. 3. The relationship between compressibility and density of lightweight composite: ○ — experimental data; (——) – regression line; (- - - -) – projected minimal and maximal values

The compressibility of less dense lightweight composite (150 kg/m^3) is also higher than that of denser one because of the fact that at larger volume of hollows in between EPS inclusions, these EPS inclusions (sized more than 5 mm), under impact of static load, can freely strain themselves, owing to partial filling of these hollows by strained EPS inclusions (Fig. 4a and b). After deloading, EPS inclusions partially recover their shape and the compressibility of lightweight composite slightly decreases.

At a higher density of lightweight composite (250–350 kg/m^3), due to better filling of hollows in between EPS inclusions by porous matrix, the tending of larger EPS inclusions (less than 20 mm) towards the area of these hollows under loads decreases, therefore, after deloading the compressibility changes but insignificantly (Fig. 5a and b).

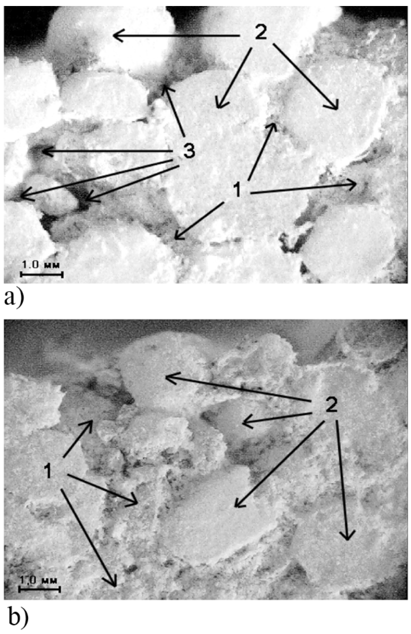

Fig. 4. The surface morphology of lightweight composite of 150 kg/m^3 density: a – unstrained; b – strained under load. 1 – porous matrix; 2 – EPS inclusions; 3 – hollows

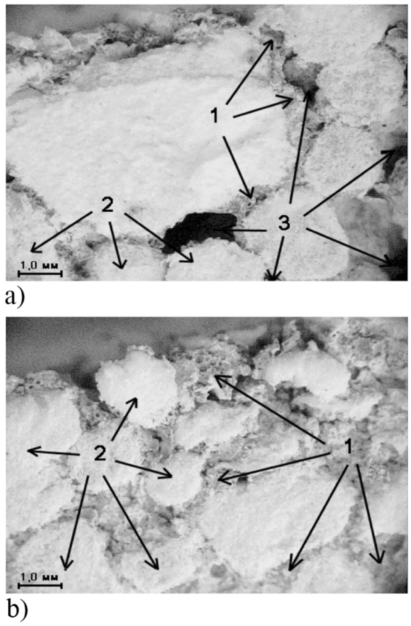

Fig. 5. The surface morphology of lightweight composite of 250–350 kg/m^3 density: a – unstrained; b – strained under load. 1 – porous matrix; 2 – EPS inclusions; 3 – hollows

3.2. Point load

The results of investigations showed that the impact of point load F_p on lightweight composite of different density ρ_a is growing along with increase in its density. This relationship can be expressed by the following equation of regression (Fig. 6):

$$F_p = 0.0984 \cdot e^{(0.0098 \cdot \rho_a)}, \quad (3)$$

with the mean square deviation S_r = 0.0431 kN (n = 30) and coefficient of determination $R^2_{F_p \cdot \rho_a}$ = 0.998, showing that the variation of point load of lightweight composite is by 99.8% preconditioned by change in its density.

Upon impact of point load on lightweight composite of 150 kg/m^3 density, the variation of compressive load reached from 0.38 to 0.49 kN, for 250 kg/m^3 density these fluctuations made from 1.10 to 1.31 kN, and for 350 kg/m^3 density – from 2.92 to 3.39 kN.

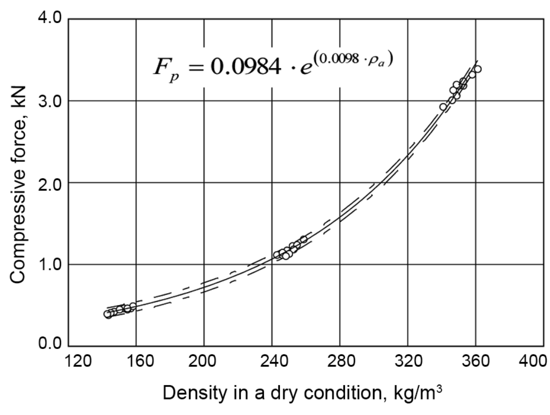

Fig. 6. The relationship between compressive force and density of lightweight composite: ○ – experimental data; (——) – regression line; (- - - -) – projected minimal and maximal values

The obtained results confirm that mean values of compressive force depend on structure of lightweight composite, i.e. on degree of filling of hollows in between EPS inclusions by porous matrix (Figs 4 and 5). Therefore, the mean values of point load at 250 kg/m^3 density of lightweight composite are higher by 62.7% than those at 150 kg/m^3 density; and at 350 kg/m^3 density, this value increases by 62.9% versus 250 kg/m^3 density and by 86.2% versus 150 kg/m^3 density.

3.3. Dynamic stiffness

The results of investigations showed that the dynamic stiffness s' of lightweight composite decreases along with decrease in its density ρ_a. This relationship can be expressed by the following equation of regression (Fig. 7):

$$s' = -29.78 + 0.457 \cdot \rho_a, \tag{4}$$

with the mean square deviation S_r = 1.653 MN/m^3 (n = 30) and coefficient of determination $R^2_{s' \cdot \rho_a}$ = 0.998, showing that the variation of dynamic stiffness is by 99.8% preconditioned by change in density.

In lightweight composite of 150 kg/m^3 density, the dynamic stiffness made 38 MN/m^3; in 250 kg/m^3 density – 96 MN/m^3; and in 350 kg/m^3 density – 131 MN/m^3.

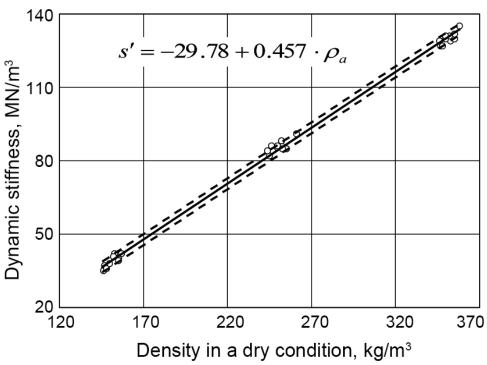

Fig. 7. The relationship between dynamic stiffness and density of lightweight composite: ○ – experimental data; (——) – regression line; (- - - -) – projected minimal and maximal values

The analysis of obtained data showed that at average of 250 kg/m^3 density, the dynamic stiffness of lightweight composite is higher by 60% versus 150 kg/m^3 density; and at average 350 kg/m^3 density, the dynamic stiffness by 70.3% exceeds the corresponding index of lightweight composite of 150 kg/m^3 density.

3.4. Reduction in normalised impact sound pressure level

The investigations showed that the normalised impact sound pressure level reduces along with increase in density of lightweight composite (Fig. 8). If at 150 kg/m^3 density the reduction in normalised impact sound pressure level was approximately 26–24 dB, then at 250 kg/m^3 density it was 20–19 dB, and at 350 kg/m^3 density was 17–16 dB.

The relationship between reduction in normalised impact sound pressure level ΔL_w and density ρ_a can be expressed by the following equation (Fig. 8):

$$\Delta L_w = 246.2 \cdot \rho_a^{-0.457}, \tag{5}$$

with the mean square deviation S_r = 0.159 dB (n = 30) and coefficient of determination $R^2_{\Delta L_w \cdot \rho_a}$ = 0.997, showing that the variation of reduction in normalised impact sound pressure level is by 99.7% preconditioned by change in density of lightweight composite.

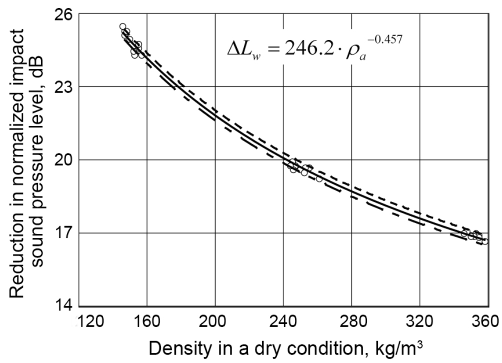

Fig. 8. The relationship between reduction in normalised impact sound pressure level and density of lightweight composite: ○ – experimental data; (——) – regression line; (- - - -) – projected minimal and maximal values

The analysis of obtained data showed that at 250 kg/m^3 density of lightweight composite, the mean value of reduction in normalised impact sound pressure level (20 dB) is lower by 20% than that at 150 kg/m^3 density (25 dB) and that at 350 kg/m^3 density this value (17 dB) decreases by 15% versus 250 kg/m^3 density and by 32% versus 150 kg/m^3 density.

Upon comparison of the obtained results on reduction in normalised impact sound pressure level of lightweight composite with the data from references (Dikavičius, Miškinis 2009; Miškinis 2010), which present impact sound insulation specifications for modern foamy and fibrous materials, one can state that the lightweight composite under investigation is an effective impact sound insulating material and can be successfully used in multilayer enclosure constructions.

The results of performed investigations (including the determination of compressibility) showed that the lightweight composite in question can be used in constructions of floating floor with load as high as 5.0 kPa (Buska *et al.* 2008; Dikavičius, Miškinis 2009; Miškinis 2010). For applications with loads exceeding 5.0 kPa, it is necessary to carry out further investigations to determine creep of lightweight composite, i.e. change in thickness under impact of corresponding dynamic loads.

4. Conclusions

The performed investigations on performance of the lightweight composite enable extending the field of its application to construction of floor and roofs.

It is established that at change in density of lightweight composite within indicated limits, its compressibility value was 2.62–0.63 mm; point load – 0.26–3.42 kN; dynamic stiffness – 35–135 MN/m^3; reduction in normalised impact sound pressure level – 26–17 dB.

It is established that the properties of lightweight composite are mostly subject to its density, which, in its turn, is determined by the following indices:

- the amount of partitions between pores in the porous cement matrix and the thickness of their walls;
- the volume of hollows, which appear in between EPS inclusions, as well as the porosity of the porous cement matrix;
- the amount of EPS inclusions per volume unit of lightweight composite;
- the particle size distribution of EPS inclusions;
- the production technology of lightweight composite (water and Portland cement ratio, the amount of AEA and etc.).

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