technical transactions

No. 2020/024

civil engineering

sciendo

Mechanical Strength Indicators of Polyurethane Adhesive in Lightweight Floor Systems

Jacek Karpiesiuk

j.karpiesiuk@doktoranci.pb.edu.pl | http://orcid.org/0000-0002-6558-5930

Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology

Scientific Editor: Marek Piekarczyk, Cracow University of Technology
Technical Editor: Aleksandra Urzędowska, Cracow University of Technology Press
Language Editors: Tim Churcher, Big Picture
Typesetting: Małgorzata Murat-Drożyńska, Cracow University of Technology Press

Received: April 14, 2020
Accepted: July 16, 2020

Data Availability Statement: All relevant data are within the paper and its Supporting Information Files.

Funding: The research was performed as part of author's own work from the Bialystok University of Technology No. WI/WB-IIL/7/2020, financed from the subsidy provided by the Ministry of Science and Higher Education.

Competing interests: The authors have declared that no competing interests exist.

Citation: Karpiesiuk, J. (2020). Mechanical Strength Indicators of Polyurethane Adhesive in Lightweight Floor Systems. *Technical Transactions*, *e2020024*. https://doi.org/10.37705/TechTrans/e2020024

Abstract

The article describes the basic features of the lightweight floor system with heat-dissipating lamellas (LFS-L) that do not require screeds and are used in the design of radiant heating. It was assumed that reactive polyurethane adhesive constitute the connection layer between the ceramic tile floor and the thermal insulation substrate, which is covered with aluminium foil. This type of construction has not been fully tested for mechanical strength. To define it, for example, using the finite element method, strength indicators of the tested adhesives which were not used in any of the previous studies discussed in this paper should be determined, such as Young's modulus E, Poisson's ratio v and linear thermal expansion coefficient α. This article presents research methods by which these data were determined. Module E and the v ratio were determined in the compression strength test of cylindrical samples of polyurethane adhesive. Coefficient α was determined by using digital image correlation in the Aramis system, placing the prepared adhesive samples in a thermal chamber.

Keywords: Young's modulus, Poisson's ratio, polyurethane adhesive, thermal expansion coefficient

1. Introduction

The construction of the lightweight floor system (LFS) without screeds and with a heating coil consists of several layers. When mounting this system on the floor, the bottom layer is usually made of extruded XPS polystyrene or expanded EPS boards. These are available uncovered or with covered tops with so-called 'metal lamellas' or aluminium foil (LFS-L). Insulation boards are grooved for the placement of heating pipes, which are most often supplied with water. Concrete surfaces are not laid and the insulation boards are covered with an adhesive or adhesive-mesh layer, constituting a connection layer with the flooring. Also, in LFS, there are so-called 'floating' floors that do not stick to the base (e.g. floor panels). The ceramic tiles, stoneware or natural stone floors are glued to the prepared base using cement, or dispersion or reactive adhesives (epoxy resins or polyurethanes). An example of the LFS-L is shown in Fig. 1, consisting of the following layers:

- flooring from ceramic tiles,
- polyurethane adhesive,
- aluminium foil,
- polyurethane adhesive,
- thermal insulation from polystyrene XPS or EPS with grooves,
- connection layer (adhesive mortar, mechanical fasteners or no fastening in the case of perfectly even surfaces),
- vapour barrier, e.g. self-adhesive foil,
- rigid substrate (concrete, wood, others).

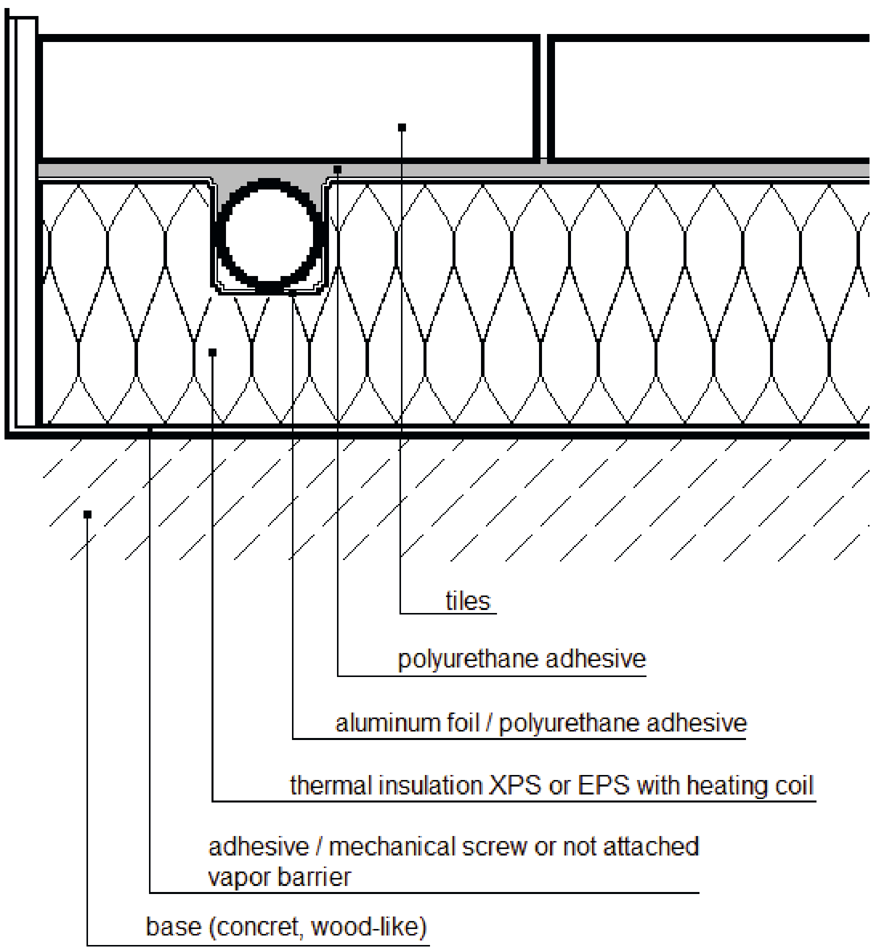

Fig. 1. Cross section of layers in SLP-L (own study)

https://doi.org/10.37705/TechTrans/e2020024

Standard NORDTEST Method NT VVS127: 2001 is dedicated to LFS with a heating coil mounted on metal heat dissipators. However, where they are not used, it is recommended to design an efficient heating system on the basis of eat efficiency based on experimental research. When laying ceramic tile flooring with metal heat diffusers attached to the thermal insulation, it is recommended to apply the appropriate connecting layer. This could be cement adhesive mortars, which require properly laying the prime metal substrate before the previous step. There are several treatments, starting with passivation and activation of the substrate, followed by its priming with epoxy resins. Only then can laying the cement mortar with reinforcement and glass fibre meshes commence. An easier solution that does not take so much time with regard to priming and strengthening the substrate is the use of polyurethane adhesives. This type of solution was subjected to mechanical strength experiments and described by (Karpiesiuk and Chyzy, 2017). They performed the following tests:

- static shear strength,
- peel strength,
- shear strength,
- tensile strength with dry conditions, long-term absorbability and frost resistance.

They confirmed the excellent quality of polyurethane adhesive for this type of surface radiator heater with lamellas.

The basic loads on layered, lightweight floors are thermal interactions generated by the heating system and standard loads – imposed and self-weighted. Under their influence, stresses and deformations occur inside the floor structure. The most important layer in the whole cross section of a light floor without screeds is an adhesive layer because it must transfer various types of internal stresses arising from external loads, including thermal interactions between layers that have significantly different strength indicators. To verify the performed experiments of mechanical strength tests described in (Karpiesiuk and Chyzy, 2017), numerical calculations should be made. These can be implemented using the finite element method (FEM). For this purpose, strength indicators of individual layer components located in the light floor system are required. Most of these are available in official specifications (Product catalogue Fibran S.A. 2011 and EN 485-2:2016+A1:2018). There is a lack of data on adhesives connecting ceramic tiles with lamellas, such as Young's modulus E, Poisson's ratio v and the coefficient of linear thermal expansion α of polyurethane adhesive - Sika BondT8 was adopted. To determine these, appropriate tests were performed in the laboratory of the Bialystok University of Technology.

2. Research methodology

After analysing the literature (Ashikuzzaman et al., 2018) and (Ferretti et al., 2016), including a doctoral dissertation (Galman, 2012) in which the uniaxial compression and tensile strength of masonry mortar under bending was tested on various types of samples (rectangular and cylindrical), it was decided to make cylindrical samples of adhesive mortars for determining the Young's modulus and Poisson's ratio of the material under axial compression. For this purpose, five samples of Sika BondT8 adhesives of equal dimensions were prepared (diameter 45 mm, height 50 mm and 10 mm). The adhesive was set in cylindrical PVC forms, as shown in Fig. 2.

After twenty-seven days, the adhesive samples were removed from the moulds and the best quality four of the five samples were accepted for testing. Axial compression tests were performed on samples smaller than those from the compression strength tests according to the standard PN-B-04500:1971 in which the diameter is 8 cm, but very close to dimensions in the standard BS EN 1015-11:2019, which are 4 x 4 cm. The BondT8 adhesive sample size was

Fig. 2. Samples of polyurethane adhesive height 50 mm and 10 mm (photos by author)

dictated by better maturing conditions at smaller diameters. Before testing the compressive strength, the adhesive samples were subjected to alignment in order to obtain even surfaces.

Initially, samples with a height of 10 mm were subjected to axial compression using a longitudinal extensometer. From these samples, an estimated compressive stress was obtained, confirming the use of appropriate testing machines. The maximum average values of compressive force and stress were obtained, which were F = 0.504 kN and σ = 0.32 N/mm² (the extensometer measurement base had a diameter of 8.5 mm). The material showed highly elastic properties up to a stress value of around 0.10 N/mm², and had characteristics close to linear, relative to deformation. The stress value grew more rapidly than the deformation, as shown in Fig. 3. After subtracting the force, the material returned to its original shape without being destroyed.

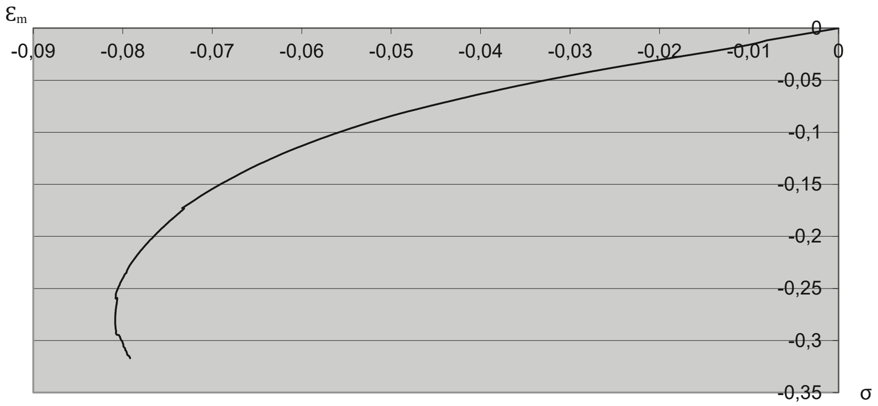

Fig. 3. Dependence of stress σ on the longitudinal strain ε_m of the 10-mm-thick polyurethane adhesive (own study)

Fig. 4. MTS 858 Mini Bionix testing machine (photo from manual)

https://doi.org/10.37705/TechTrans/e2020024

The test used a dynamic two-axle testing machine MTS 858 Mini Bionix with a hydraulic drive mounted on a 359 load frame with a 4-fold smaller range of axial loads ± 25 kN, Fig. 4.

After the initial tests were completed, target tests were performed using two extensometers attached to each of the 50 mm-high polyurethane adhesive samples both transversely and longitudinally to the compression axis. Extensometers were attached to a measuring transducer with the results readout on a computer screen. The longitudinal base of the extensometer was constant and had a diameter of 39 mm. The following extensometer types were used:

- longitudinal Instron 2620, with a measurement accuracy of 0.15% FSD (full-scale deflection)
- Epsilon 3542050M-025-HT1 transverse, with a measurement accuracy of 0.15% FSD

Extensometers fixed with rubber O-rings were used to measure transverse and longitudinal deformations during the compressive strength test of the prepared samples in order to determine the Poisson's ratio of the adhesive mortars. The method of attachment is shown in Fig. 5.

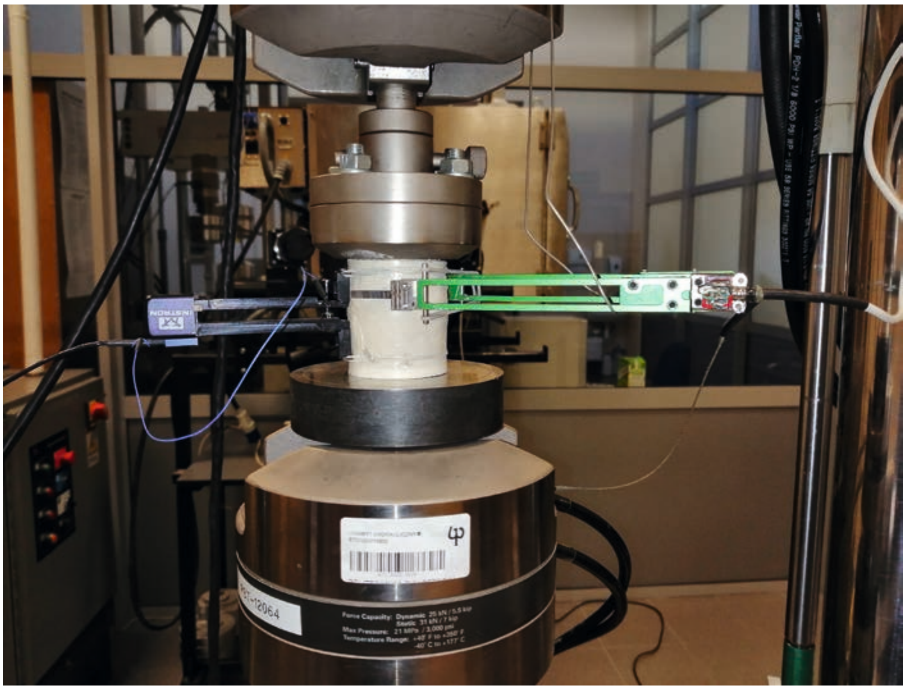

Fig. 5. One of the adhesive mortar samples with extensometers for measuring deformations during the compressive strength test (photo by author)

The dependence of longitudinal deformation ε_m on adhesive stress was then tested on two samples, using the ARAMIS 3D 4M vision system by the method of Digital Image Correlation (DIC), and by cooperation with the MTS testing machine. A set of DIC system devices was used for non-contact, three--dimensional measurements of deformations caused by static and dynamic loads. The objective of this method was to analyse and calculate displacements and document material deformations. The graphical representation of the obtained test results provides the opportunity to fully understand the behaviour of the tested object. Figure 6 shows this cooperation.

The same method was used to determine the coefficient of linear thermal expansion α on 10 x 10 x 80 mm samples prepared in special forms (Fig. 7) and placed in the environmental chamber MTS 651.05E-02 (Fig. 8). Due to the difficulty of directly applying a random pattern of coloured spray paint to the polyurethane, ceramic pins were inserted into the samples and covered with paint. The chamber allows static and dynamic strength tests to be performed in simple and complex states of stress under reduced and elevated temperatures. The cooperation of the thermal chamber and the DIC set is shown in Fig. 9.

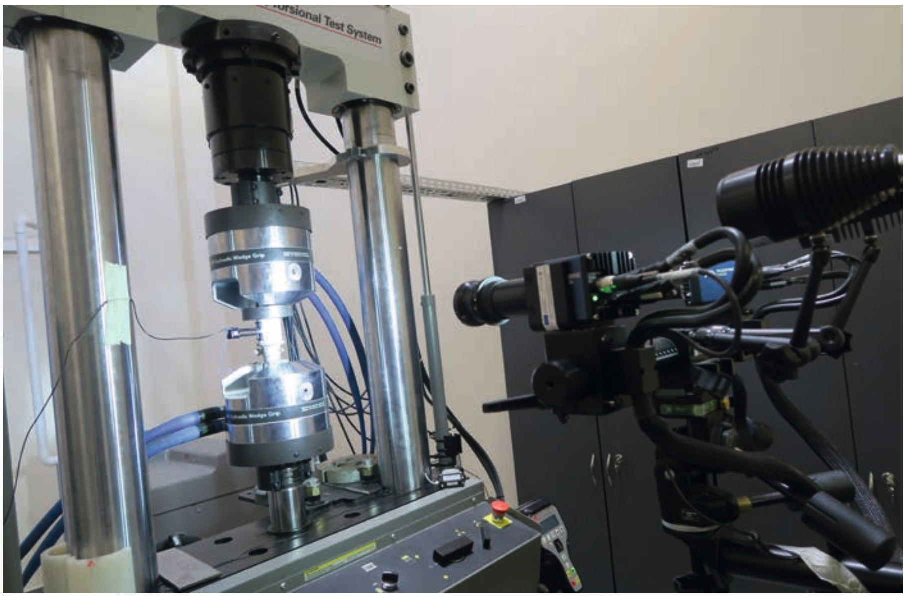

Fig. 6. Measurement of ε_m deformation of the sample using the ARAMIS 3D 4M vision system (photo by author)

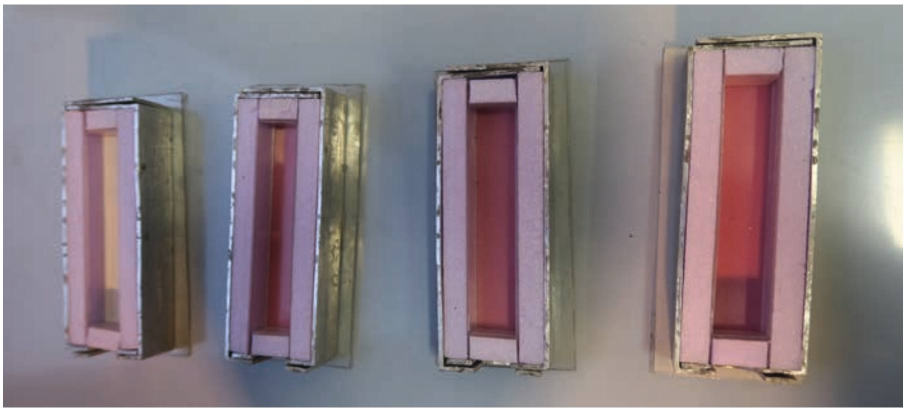

Fig. 7. Forms for preparing 10 x 10 x 80 mm polyurethane adhesive samples (photo by author)

Fig. 8. MTS 651.05E-02 environmental chamber with assembly platform (photo by author)

The tests performed by Zajac (2018) on cylindrical samples of adhesives measuring 28 mm (diameter) by 120 mm (length) in a special thermal chamber using the WA-10 induction sensor for measuring displacements connected to a computer equipped with a data acquisition program, showed that the value of

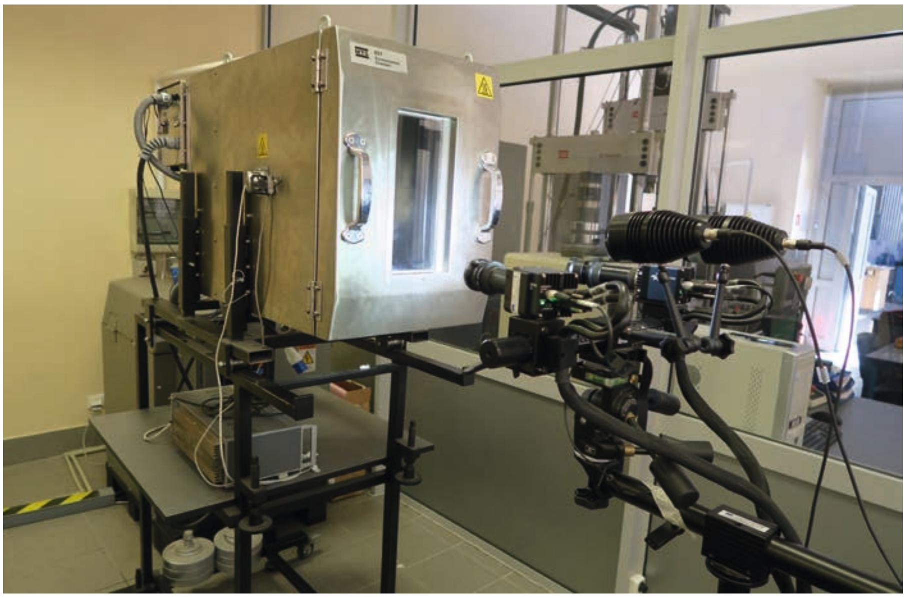

Fig. 9. ARAMIS 3D 4M vision kit and MTS 651.05E-02 thermal chamber to factor testing (photo by author)

the linear expansion coefficient α in polyurethanes above the glass transition temperature (T_g) had a slight upward trend. The T_g height in polyurethane was reached at a temperature much lower than 0°C, e.g. polyurethane PT had a T_g of about –30°C, and PS was –40°C. Depending on the type of polymer tested by Zajac (2018), the size α was on average in the range of $126–210 \cdot 10^{-6}$ 1/°C for temperatures of 40–100°C, respectively, at an initial temperature of 20°C (measurement differences of three samples of each adhesive were in coefficient of variation 6.3–9.8%). Differences in the strain distributions of stiff mineral and flexible polyurethane adhesives in DIC observation have also been researched by Kwiecien et al. (2017).

3. Research results

The main purpose of the research was to determine the Poisson's ratio ν, Young's modulus E and the linear thermal expansion coefficient α of the polyurethane adhesive on the basis of tests performed on the samples prepared as described above.

Measurements of the coefficient α were performed on the samples described above after reaching the set temperature values. The study was started at 20°C and ended at 50°C. The first elongation measurement was conducted at 30°C. The duration of testing individual samples was 3–5 hours. The results of the coefficient α were determined from the formula (1) of the EN ISO 10545-8:2014.

$$\alpha = \frac{\Delta L}{L_0 \cdot \Delta T} \tag{1}$$

ΔL – increase in the length of the test sample between the tested temperature ranges [mm]
L_0 – length of test sample at ambient temperature (20°C) [mm]
ΔT – temperature increase (5°C intervals, from temperature 30°C) [°C]

The dependence of elongation to the time when testing one of the samples is shown in Figure 10 and summarized in Table 1, assuming average values together with their coefficients of variation. The measuring base had a diameter of 51 mm. Calculations were made at 5°C intervals, measured from 30–50°C.

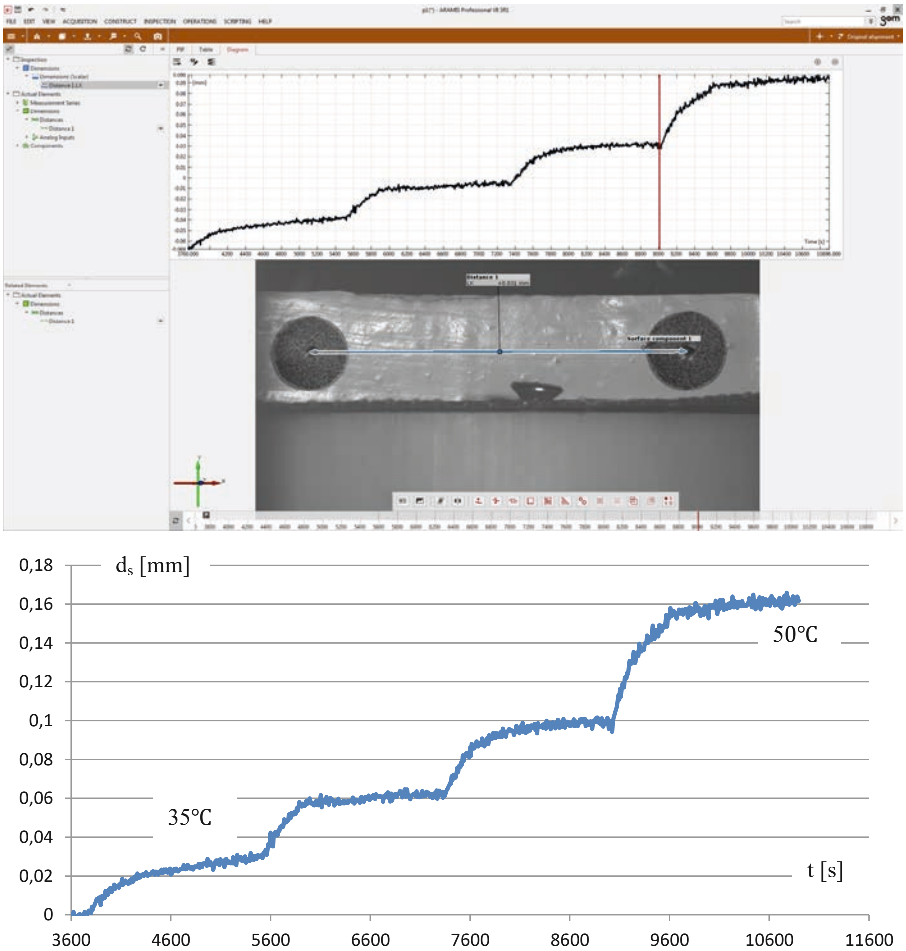

Fig. 10. View one of the tested polyurethane samples and graph of elongation versus test duration (own study)

To determine the material stress, the calculation formula (2) was used:

$$\sigma = \frac{F}{A} \tag{2}$$

σ – material stress [MPa]
F – compressive force [N]
A – area of a given sample calculated as a circle, equal to πr^2 [mm^2]

Based on formula (2), the quadratic functions characterising the relationship of stress σ to longitudinal deformation ε_m in the compression of polyurethane adhesive were determined. Samples of polyurethane adhesive were denoted as P1–P6, including two tests, which additionally carried out using the Digital Image Correlation method in the Aramis system (P5, P6).

A cumulative summary of six designated polynomial functions of the second degree, determined by the method of least squares, shows the dependence of longitudinal strain ε_m on compression stress σ in MPa of each sample is shown in Fig. 11. This figure also includes two functions, researched by the Aramis vision system, with a maximum stress of not more than 0.1 MPa.

The same method determined the polynomial function, taking the arithmetic mean of the test results from individual samples for calculations, as shown in Fig. 12.

When it is difficult to determine a part of the rectilinear quadratic function of the relationship between stress and deformation, to determine the value of the immediate modulus of longitudinal stiffness E, it is necessary to lead the tangent or secant at point x = 0 to the designated function P *Evola*, shown in Fig. 12 as given in (Bednarski et al., 2014) and (Boronski, 2004). A second-order polynomial in methodology to determine the elastic properties of low anisotropic

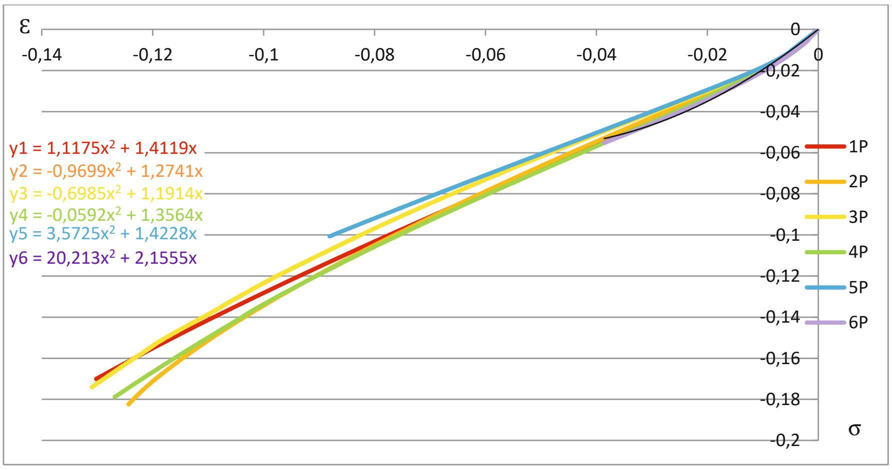

Fig. 11. Dependence of σ on ε polyurethane adhesive P of six samples under compression (own study)

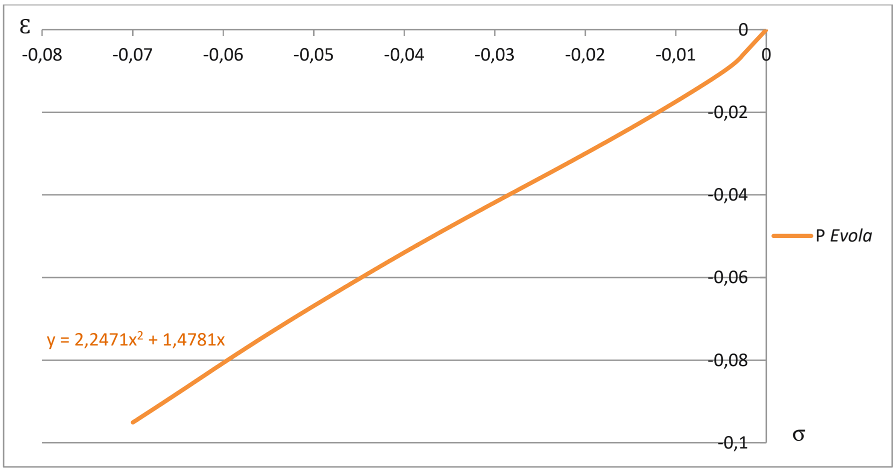

Fig. 12. Dependence of σ on ε polyurethane adhesive P, as P *Evola* function under compression (own study)

rocks with the nonlinearity of elasticity from a single uniaxial compression (Nejati et al., 2019) was used as an appropriate function to fit the data points because increasing the order of the polynomial practically does not change the tangent values. Additionally, the data of strain are fitted to a second-order polynomial using the least-squares approach. The tangent values of the elastic constants are easily obtained from the derivatives of the determined functions. The calculation of the tangent to the function graph is shown by equation (3), as is suggested in literature (Nejati et al., 2019), where the tangent elastic constants are obtained using the derivatives of the stresses with respect to their corresponding strain:

$$y_1 - y(x_0) = y'(x_0) \cdot (x - x_0) \tag{3}$$

Based on the polynomial P *Evola* function of polyurethane adhesive, the Young's modulus E was determined from formula (3), which is:
P *Evola* function under compression is:
$y = 2.2471x^2 + 1.4781x$, where
$x_0 = 0$
$y' = 4.4942x + 1.4781$
$y'(x_0) = 1.4781$
$y(x_0) = 0$, so
$y_{S1} - 0 = 1.4781 \cdot (x - 0)$, hence
$y_{S1} = 1.4781x$
and Young's modulus is:
$E_{eP} = \mathrm{tg}\alpha = \frac{y}{x} = 1.4781\ \mathrm{MPa} \approx 1.50\ \mathrm{MPa}$

Figure 12 shows the dependence of σ on ε_m of P *Evola* polyurethane adhesive only up to stress values of 0.016 MPa or 0.022 MPa, as shown in Figs. 13 and 14. These reflect the sum of stresses arising from service loads in the range of 2–7.5 kN/m² following Hooke's law and thermal loads, according to linear expansion law, defined by formula (4).

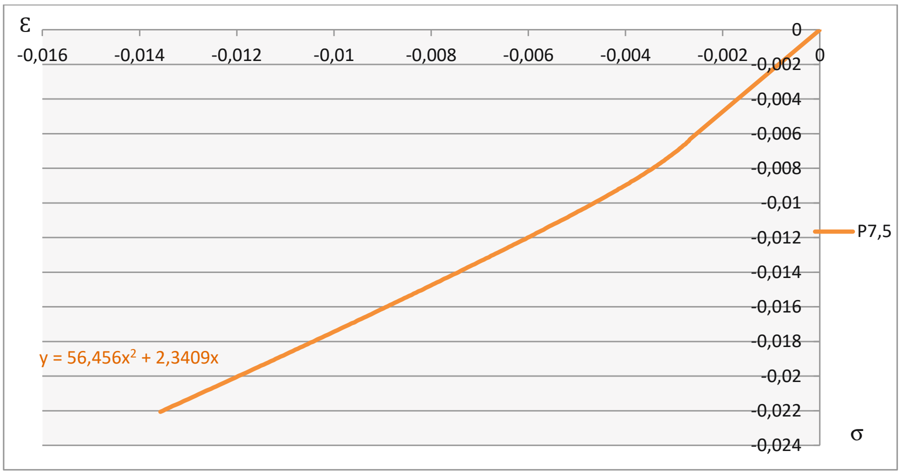

Fig. 13. Dependence σ on ε of polyurethane adhesive P, as a function of P7.5 under compression, on the imposed load 7.5 kN/m² (own study)

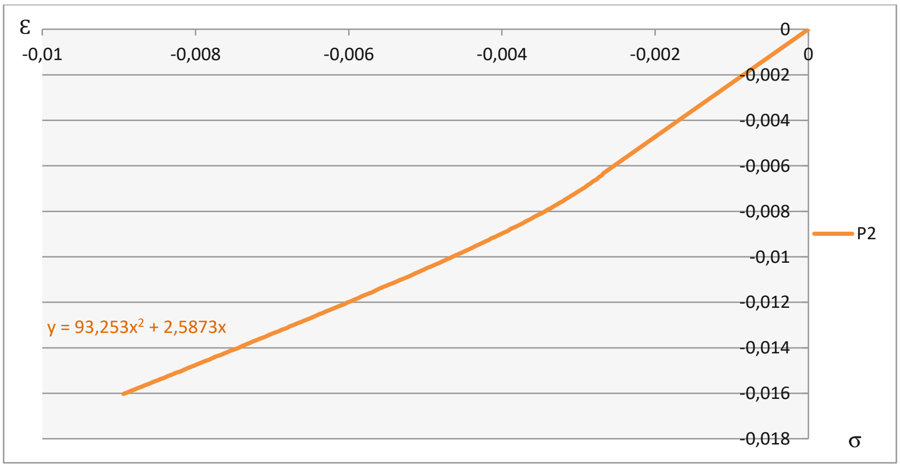

Fig. 14. Dependence σ on ε of polyurethane adhesive P, as a function of P2 under compression, on the imposed load 2.0 kN/m² (own study)

$$\sigma_c = \sigma_u + \sigma_t \tag{4}$$

σ_c – the sum of compressive stresses from imposed and thermal loads [MPa]
σ_u – compressive stresses from imposed loads [MPa]
σ_t – compressive stress from thermal influences [MPa]
where σ_u specifies the formula (5) and σ_t formula (6)

$$\sigma_u = \mathrm{F}_u \tag{5}$$

F_u – imposed load – the maximum admissible according to the standard EN 1991-1-1:2004 was adopted for areas generally available for a crowd at the level of 7.5 kN/m² or in living rooms 2 kN/m²

$$\sigma_{u_1} = 7{,}500\ [\mathrm{N/m^2}] = 0.0075\ [\mathrm{MPa}] \text{ or } \sigma_{u_2} = 2{,}000\ [\mathrm{N/m^2}] = 0.002\ [\mathrm{MPa}]$$

$$\sigma_t = \mathrm{E}\cdot\frac{\Delta l}{l} = \mathrm{E}\cdot\alpha\cdot\Delta T \tag{6}$$

https://doi.org/10.37705/TechTrans/e2020024

E – Young's modulus of polyurethane adhesive was assumed as 2.35 MPa and 2.60 MPa, which are equal to the coefficient b values of polynomial functions shown in Figs. 13 and 14, which results from calculations carried out by the formula (3); these results refer to tests for 0.022 MPa and 0.016 MPa compressive stress values, respectively

α – coefficient of thermal expansion of polyurethane adhesive read from Table 1 – 0.000130 = 130 · 10^{-6} 1/°C at 40°C (average temperature under the floor heating floor, at the maximum possible medium temperature in the heating coil)

ΔT – temperature difference (the maximum possible difference in temperature of the adhesive layer in LFS is 45°C, assuming the initial temperature of the medium as 5°C and the maximum allowable average temperature of the medium in the heating pipe as 50°C, calculated in Karpiesiuk and Chyzy (2017) and confirmed as being appropriate in Werner-Juszczuk (2018).

$\sigma_{t1} = 2.35 \cdot 0.000130 \cdot 45 = 0.0137$ MPa or $\sigma_{t2} = 2.60 \cdot 0.000130 \cdot 45 = 0.0152$ MPa

hence from formula (4) we have:

$\sigma_{c1} = 0.0075 + 0.0137 = 0.0212$ MPa or $\sigma_{c2} = 0.002 + 0.0152 = 0.0172$ MPa

Ultimately, the average value of stress in LFS from imposed loads in the range of 2–7.5 kN/m2 and thermal influences was adopted as the arithmetic mean, which is:

$$\sigma_c = (\sigma_{c1} + \sigma_{c2})/2 = (0.0212 + 0.0172)/2 = 0.019 \approx 0.02 \text{ MPa}$$

For this average stress value σ_c, the graph of dependence of stress on the deformation of the polyurethane adhesive P is shown in Fig. 15.

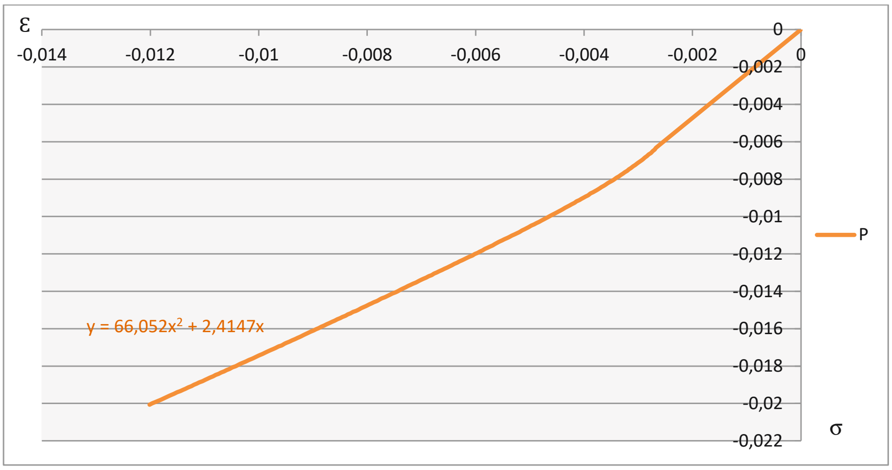

Fig. 15. Dependence σ on ε of polyurethane adhesive, as a P function in compression, on the sum of stresses (at average imposed and thermal loads) in LFS (own study)

For adhesive P on the basis of the calculated 2nd-degree polynomial function and shown in Fig. 15 at average values of the imposed and thermal load, Young's modulus E from formula (3) is:

P function under compression is:
$y = 66.052x^2 + 2.4147x$. and Young's modulus is:

$E_P = \text{tg}\alpha = \frac{y}{x} = 2.4147 \text{ MPa} \approx 2.50 \text{ MPa}$

Poisson's ratio is the absolute value of the ratio of transverse deformation to the corresponding axial (longitudinal) deformation resulting from the evenly distributed axial stress below the material proportionality limit. This is described by formula (7):

$$\nu = -\frac{\varepsilon_n}{\varepsilon_m} \tag{7}$$

ν – Poisson's ratio
ε_n – transverse deformation
ε_m – longitudinal deformation

The coefficient ν is estimated by carrying out tests on the samples under tensile or compressive forces following the standard ASTM E132 – 17 for uniaxial stress. Under the influence of the applied force, the homogeneous, isotropic material has elastic properties, determined by, *inter alia*, Poisson's ratio ν, Young's modulus E and Kirchhoff G. When determining Young's modulus by the standard ASTM E111 – 17, initial readings are not included in the calculations, due to possible small shifts during the first small load increase. However, the individual assessment of the strength characteristics of materials depends not only on their chemical composition but also on the procedure and apparatus used in the tests. The average arithmetic value of the Poisson coefficient of elastic compression stresses of the polyurethane adhesive was assumed in the calculations for each of the samples. Additionally, the characteristics of the function close to linear were taken, where stable numerical values were achieved in a given research sample. An example of the dependence of stress on the ratio of transverse to longitudinal deformation in strain gauges is shown in Fig. 16.

The results of determining Young's modulus E_p, Poisson's ratio ν_{avg} and coefficients of linear thermal expansion α_{evg} (temperature-dependent) of the Sika BondT8 polyurethane adhesive with regard to imposed and thermal loads of the lightweight floor system are given in Table 1.

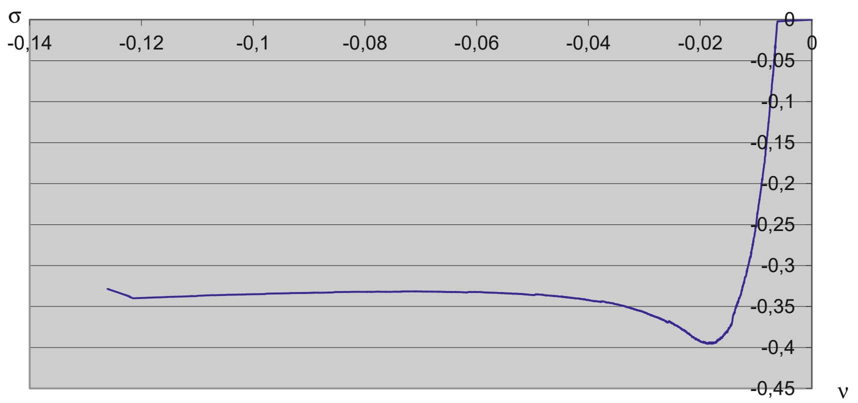

Fig. 16. Dependence of stress σ on the ratio of transverse deformation to longitudinal ν of Sika BondT8 polyurethane adhesive (own study)

Table 1. The value of EP, ν_{avg} and α_{avg} of the Sika BondT8 polyurethane adhesive (in brackets is the coefficient of variation for α_{avg}) (own study)

Type of adhesive	α_{avg} [10^{-6}/°C]	Samples No.	E_i [MPa]	E_P [MPa]	ν_i	ν_{avg}
P (BondT8)	109–**30°C** (5.7%)	P1	1.4119	2.50 (1.5–P *Evola*)	0.30	0.32
	120–**35°C** (6.3%)	P2	1.2741		0.33	
	130–**40°C** (6.9%)	P3	1.1914		0.32	
	152–**45°C** (7.4%)	P4	1.3564		0.33	
	239–**50°C** (9.1%)	P5	1.4228		–	
	–	P6	2.1555		–	

α_{evg} – average coefficient of linear thermal expansion of the P adhesive, depending on temperature
E_i – Young's modulus of a given sample
E_P – Young's modulus of P adhesive in LFS at σ = 0.02 MPa (in brackets EP value at σ to 0.1 MPa)
ν_i – sample Poisson's ratio
ν_{avg} – average assumed Poisson's ratio of P adhesive

4. Conclusions

Compressive strength tests of cylindrical samples enabled the determination of Sika BondT8 polyurethane adhesive strength indexes, specifically Young's modulus, and Poisson's ratio. Coefficients of linear thermal expansion, dependent on temperature, were determined by placing samples in a thermal chamber and using digital image correlation in the Aramis system. With this data, they can be used in calculations of the mechanical strength of a Lightweight Floor System (LFS) with a heating coil in the Finite Element Method, as well as for all other calculations needed. In addition, a function called P *Evola* has been designated to characterize the Sika BondT8 polyurethane adhesive. The determined average stress value, as the maximum in a lightweight floor system with a heating coil without screeds at the same time as the imposed and thermal loads, is σ = 0.02 MPa. This stress corresponds to a deformation of $\varepsilon \approx 0.012$. Due to the extremely high elasticity of the polyurethane adhesive at low stress in the samples used in the compressive strength test, it is recommended to perform a tensile strength test of the polyurethane adhesive at the actual thickness of its use, 1-2 mm. This recommendation is intended to help lead to a confirmation or correction of the results obtained by Young's modulus and Poisson's ratio of polyurethane adhesives under axial compression.

References

ASTM E132 – 17. Standard Test Method for Poisson's Ratio at Room Temperature.

ASTM E111 – 17. Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus.

Ashikuzzaman, Md., Tarif Uddin, A., Zahidul, A., Altaf Hossain, Md. (2018). Effect of Brick Forming Load on Mechanical Properties of FlyAsh Bricks. *Tr Civil Eng & Arch*, *3*(2), 1–6. TCEIA.MS.ID.000157. DOI: 10.32474/TCEIA.2018.03.000157

Bednarski, L., Sienko, R., Howiacki, T. (2014). Oszacowanie wartosci i zmiennosci modulu sprezystosci betonu w istniejacej konstrukcji na podstawie ciaglych pomiarow in situ. *CWB*, 6, 396–404.

Boronski, D. (2004). The effect of the method of determination of Young's modulus on the estimation of fatigue life of structural elements. *Journal of theoretical and applied mechanics*, *42*(2), 269–83.

BS EN 1015-11:2019. Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar.

EN 1991-1-1:2004. Eurocode 1: Actions on structures – Part 1-1: General actions - Densities, self-weight, imposed loads for buildings.

EN 485-2:2016+A1:2018. Aluminium and aluminium alloys. Sheet, strip and plate. Mechanical properties.

EN ISO 10545-8:2014. Ceramic tiles. Determination of linear thermal expansion.

Ferretti, F., Incerti, A., Ferracuti, B., Mazzotti, C. (2016). Diagonal compression tests on masonry panels strengthened by FRP and FRCM. In *Proc. of SAHC 2016*, 13-15. Leuven, Belgium.

Galman, I. (2012). PhD Thesis: *Sciany z ceramicznej cegly pelnej cyklicznie sciskanej w swej płaszczyznie lub zginane prostopadle do plaszczyzny*. Gliwice: Katedra Konstrukcji Budowlanych. Wydzial Budownictwa, Politechnika Sląska.

Karpiesiuk, J., Chyzy, T. (2017). Wyniki eksperymentalnych badan rozkladu temperatury grzejnikow plaszczyznowych o lekkiej konstrukcji bez jastrychow. *Rynek Instalacyjny*, *11*(XXV), 45–50.

Karpiesiuk, J., Chyzy, T. (2017). Wyniki wybranych badań wytrzymałości międzyfazowej lekkiego grzejnika płaszczyznowego z rozpraszaczami ciepła. *Civil and Environmental Engineering/Budownictwo i Inżynieria Środowiska*, *8*(3), 123–132.

Kwiecien, A., Hojdys, L., Krajewski, P., Tekieli, M. (2017). *Differences in strain distribution of stiff mineral and flexible polyurethane adhesives in DIC observation*. COST Action TU1207, Next Generation Design Guidelines for Composites in Construction. Retrieved from https://sites.google.com/a/sheffield.ac.uk/tu1207/dissemination/state-of-the-art. (date of access: 2020/02/15).

Nejati, M., Dambly, M.L.T., Saar, M.O. (2019). A methodology to determine the elastic properties of anisotropic rocks from a single uniaxial compression test. *Journal of Rock Mechanics and Geotechnical Engineering, 11*, 1166–1183.

NORDTEST Method NT VVS127: UDC 697.1: Approved 2001-11. Floor heating systems. Design and type testing of waterborne heat systems for lightweight structures.

PN-B-04500:1971. Zaprawy budowlane – Badania cech fizycznych i wytrzymalosciowych.

Product catalogue Fibran S.A. (September 2011). Extruded polystyrene thermal insulation FIBRANxps.

Werner-Juszczuk, A.J. (2018). Experimental and numerical investigation of lightweight floor heating with metallised polyethylene radiant sheet. *Energy & Buildings, 177*, 23–32.

Zając, B. (2018). *Scinane polaczenia klejone sztywne i podatne pracujące w podwyższonej temperaturze.* Kraków: Politechnika Krakowska.