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ORIGINAL PAPER

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THE MAIN STRENGTH MATERIAL PARAMETERS OF DEFORMABLE CEMENT ADHESIVES

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ABSTRACT

The deformable cement adhesives types C2S1 and C2S2 are usually used to glue ceramic slabs onto so-called critical substrates (other than concrete), including under changing weather conditions. The declared strengths of these adhesives attached to substrates can be found in the manufacturer's standards and declarations. The use of cement adhesives on surfaces other than concrete or in other applications, such as a lightweight heated floor system (LHFS), should meet safety standards. To determine this, basic strength parameters for deformable adhesives, which have not been specified until now, need to be set. For this purpose, many analyses were performed, such as tensile and compressive strength tests, as well as the measurement of displacements in the thermal chamber, using, for example, digital image correlation and extensometric techniques. It was possible to define the main strength parameters of deformable adhesives, such as Young's modulus (E), Poisson's ratio (ν) and linear thermal expansion coefficient (α). These multiple measuring techniques were able to authenticate the obtained results, determining the maximum compressive strength of deformable adhesives, as well as longitudinal and transverse deformations. The research material parameters E, ν and α can be used for the calculation of LHFS with a heating coil, as well as for other building partitions or on critical substrates (different from concrete), using some of the many numerical methods available.

Keywords: Young's modulus, Poisson's ratio, thermal expansion coefficient, deformable cement adhesives

INTRODUCTION

One of the many loads that occur in a lightweight heated floor (generated by the heating system) or in an ETICS system (influenced by solar heat) are thermal actions as well as standard loads – imposed and self-weighted. Both of these systems are considered lightweight because the thermal insulation is not covered with a thick layer of concrete, but directly with an adhesive and mesh layer, and then with ceramic tiles, plaster or other types of thin floor covering, as described in the literature (Nordic Council of Ministers [NT], 2001; Elektra Kardo, 2018; Flooré, 2019). Under the influence of the mentioned loads, stresses and deformations occur inside the floor/wall structure. The most important layer in the entire section of the lightweight floor or wall is the adhesive mortar. It connects the top and bottom layers of a Lightweight Heated Floor System (LHFS).

It has to transfer various types of internal stresses arising from external loads, including thermal actions. To determine these stresses, a number of experiments had to be performed as described in papers by Karpiesiuk

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(2020a, 2020b) and Karpiesiuk and Chyzy (2020a, 2020b). In order to confirm whether the experimentally determined strength test results meet the load capacity criteria of the LHFS component materials, numerical calculations must be performed. These can be realised using the Finite Element Method (FEM) or other numerical methods. To apply these methods, the strength parameters of the materials contained in the LHFS are necessary. The parameters of the ceramic tile, glass fibre mesh or thermal insulation are written in Table 1 together with a list of literature.

Table 1. The strength material parameters from the literature

Material	Young's modulus (E) [MPa]	Thermal expansion (α) [$10^{-6} \cdot K^{-1}$]	Poisson's ratio (v) [-]
Ceramic tile	50 000	8	0.16
Anisotropic glass fibre mesh type E, GFRP	60 000–70 000	4.7	0.22
XPS 300	13–15	70–75	0.20
EPS 200	7.8	55	0.17

Source: Shulmeister (1997); Artemenko (2003); Wambua, Ivens and Verpoest (2003); Perepelkin (2005); Dow Chemical Company (2008, 2014); Piekarczyk, Kata, Lis and Galos (2008); Fibran (2010); Elragi (2012); Padade and Mandal (2012); European Committee for Standardisation [CEN] (2014, 2015, 2016a, 2016b).

The material parameters of the deformable adhesives type C2S1, C2S2 and their composite with a glass fibre mesh – such as Young's modulus, thermal expansion and Poisson's ratio, which bond the ceramic floor to the thermal insulation – are not available in the literature. These parameters are essential for numerical calculations using the finite element method (FEM). The determination of these material parameters can be achieved by several test methods. Ideally, these parameters should be confirmed using multiple methods to verify the obtained data.

MATERIAL AND METHODS

The materials tested are deformable C2S1 and C2S2 adhesives. Various tests were performed primarily to determine material parameters such as Young's modulus, Poisson's ratio and the thermal expansion coefficient of the C2S1 and C2S2 deformable adhesives. Additionally, the compressive strengths of these adhesives were tested. The research was conducted in the laboratories of the Białystok University of Technology and the Kraków University of Technology.

Young's modulus and Poisson's ratio of C2S1 and C2S2 adhesives were determined using the following methods:
– the tensile strength of C2S1 adhesive was tested using dumb-bell test specimens and extensometers;
– the compressive strength of the C2S1 and C2S2 adhesives were tested using cylindrical samples and extensometers.

The thermal expansion coefficient of the C2S1 and C2S2 adhesives were tested using the following methods:
– the adhesives were tested using the Digital Image Correlation (DIC) method, placing their rectangular samples in a thermal chamber;
– the adhesives were tested using an inductive sensor, placing their cylindrical samples in the special author's thermal chamber.

Research to determine the tensile strength data for Sika Ceram 255 cement adhesive mortar C2S1 was performed in a laboratory of the Białystok University of Technology.

Dumb-bell test specimens of C2S1 adhesive was used for these tests, performed following the ISO 527-2:2012 standard (International Organisation for Standardisation [ISO], 2012). One of the four specimens and its dimensions is shown in Figure 1. The measurement base was 20 mm.

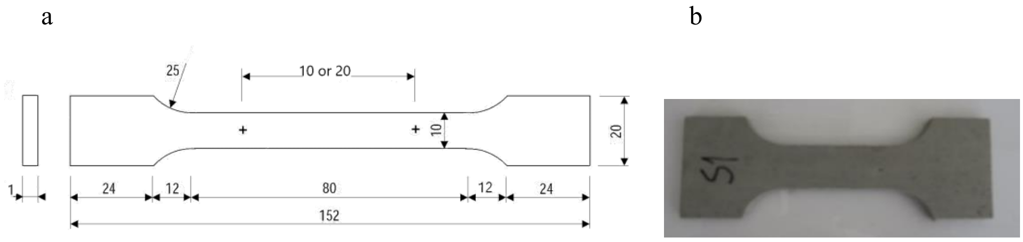

Fig. 1. Dumb-bell test specimens: a – samples dimensions [mm], according to EN ISO 527-2 standard (ISO, 2012); b – sample of C2S1 adhesive

Source: own work.

A dynamic two-axis MTS 858 Mini Bionix testing machine was used to research the displacement measurements of C2S1, which worked with Instron 2620 and Epsilon 3542050M-025-HT1 extensometers (Fig. 2). The dependence of longitudinal deformation ($\mathcal{E}_m$) on tensile stress was studied on three samples.

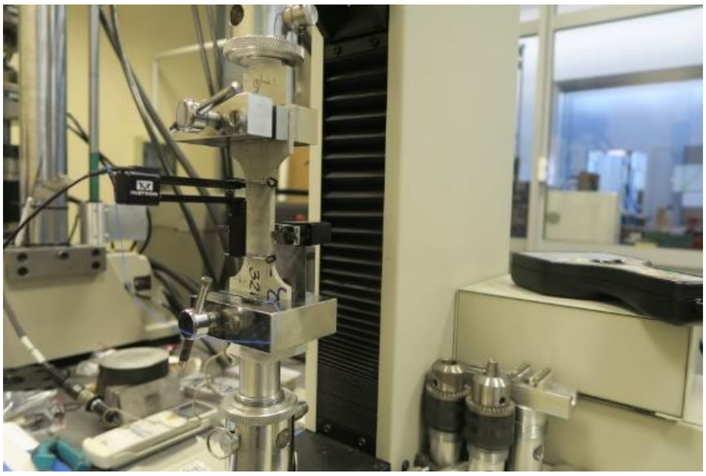

Fig. 2. Measurement of longitudinal deformation ($\mathcal{E}_m$) and transverse deformation ($\mathcal{E}_n$) using extensometers

Source: own photo.

The experimental compressive strength of the C2S1 and C2S2 adhesives, as described in (Karpiesiuk & Chyzy, 2020a), allows for determining the stress-deformation functions of the C2S1 adhesive mortar (specifically Sika Ceram 255) and C2S2 adhesive mortar (specifically BASF Flex-mortel), along with their Young's modulus and Poisson's ratios. The experimental research was supported by mathematical verification calculations. The article (Karpiesiuk & Chyzy, 2020a) provides detailed information on the preparation and execution of this research.

The research on the linear expansion coefficient was carried out in two stages. The first, preliminary stage, was performed at the Białystok University of Technology, using the digital image correlation (DIC) method in the Aramis system, as described earlier in (Karpiesiuk, 2020a). The next stage was performed at the Kraków University of Technology, using an inductive sensor to measure material displacements.

In the preliminary studies for determining the linear thermal expansion coefficient of C2S1 Sika Ceram and C2S2 BASF Flex-mortar adhesive mortars (using the DIC method), 10 × 10 × 80 mm samples were used. They were placed in an MTS 651.05E-02 environmental chamber (Fig. 3), where cooperation with the DIC set was visible. The samples were covered in a random pattern of coloured spray paint. The tests started at 20°C and ended at 70–80°C. The first displacement measurement was conducted at 30°C. The testing time of each specimen was 1–3 h.

Fig. 3. ARAMIS 3D 4M vision set and MTS 651.05E-02 thermal chamber to research the thermal expansion coefficient (α) of the C2S1 adhesive

Source: own photos.

The second part of the research on the thermal expansion coefficient (α) includes the experiments carried out by Zając (2018) on cylindrical specimens. It was conducted in a special thermal chamber using WA-10 induction sensors for displacement measurement and connected to a computer equipped with Catman Easy 3.1 data acquisition software. Based on these experiments, verification tests of the coefficient α were performed at the Kraków University of Technology for deformable adhesives. For this purpose, cylindrical samples with a diameter of 28 mm and length of 120 mm were prepared from C2S1 and C2S2 adhesives, as shown in Figure 4. The tests started at 0°C and ended at 80°C.

a b

Fig. 4. Cylindrical samples of C2S1-S1 adhesive (a) and C2S2-S2 adhesive (b)

Source: own photos.

RESULTS AND DISCUSSION

The main objective of the tensile strength research, using dumb-bell samples of C2S1 adhesive, was to determine Young's modulus (E). For this purpose following formula was used:

$$\sigma = \frac{F_r}{A}, \tag{1}$$

where:
σ – stress in the adhesive [MPa],
F_r – tensile force [N],
A – cross-section of the sample [mm^2].

The quadratic functions characterising the dependence of stress (σ) on longitudinal deformation ($\mathcal{E}_m$) at the tensile strength of adhesives were determined from Eq. (1).

Young's longitudinal modulus of elasticity was determined using Hooke's law:

$$\sigma = E \cdot \mathcal{E}. \tag{2}$$

An example of C2S1 adhesive stress dependence on the longitudinal deformation in extensometer research is shown in Figure 5. In the test, the three samples of the C2S1 adhesive averaged a maximum tensile stress ($\sigma_{\text{max avg}}$) of 1.35 MPa, average longitudinal tensile deformation ($\mathcal{E}_m$) of 0.0006 and average elasticity modulus ($E_{c\text{ avg}}$) of 5,950 MPa.

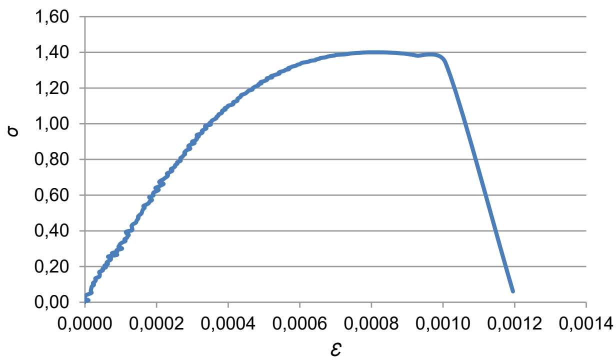

Fig. 5. Dependence of stress (σ) to the longitudinal deformation ($\mathcal{E}$) one of the C2S1 adhesive

Source: own work.

Four different function graphs were made to determine the values of Young's modulus of deformable C2S1 and C2S2 cement adhesives in the article (Karpiesiuk & Chyzy, 2020a). The graphs of the *S*1 and *S*2 functions were defined only based on experimental tests of the compressive strength of cylindrical samples. The graphs of the *S*1 *Evola* and *S*2 *Evola* functions are additionally based on the mathematical formulas, the so-called "Madrid parabola" (Eqs 3 and 4), which verified the experimental results through mathematical analyses. The graphs of the four functions *S*1, *S*2, *S*1 *Evola* and *S*2 *Evola* are shown in Figure 6. *S*1 *Evola* and *S*2 *Evola* were accepted as the final results (i.e., those after mathematical verification, considering them to be closest to the truth).

For calculating compressive stress in cement adhesive mortar C2S1 following formula was used:

$$\sigma_{S1} = 15.5\left[1-\left(1-\frac{\varepsilon_{S1}}{0.0051}\right)^2\right], \tag{3}$$

where:
σ_{S1} – compressive stress in C2S1 adhesive, corresponding to the deformation ε_{S1},
ε_{S1} – deformation of C2S1 adhesive from the research.

For calculating compressive stress in cement adhesive mortar C2S2, the following formula was used:

$$\sigma_{S2} = 13.7\left[1-\left(1-\frac{\varepsilon_{S2}}{0.0126}\right)^2\right], \tag{4}$$

where:
σ_{S2} – compressive stress in C2S2, corresponding to the deformation ε_{S2},
ε_{S2} – deformation of C2S2 adhesive from the research.

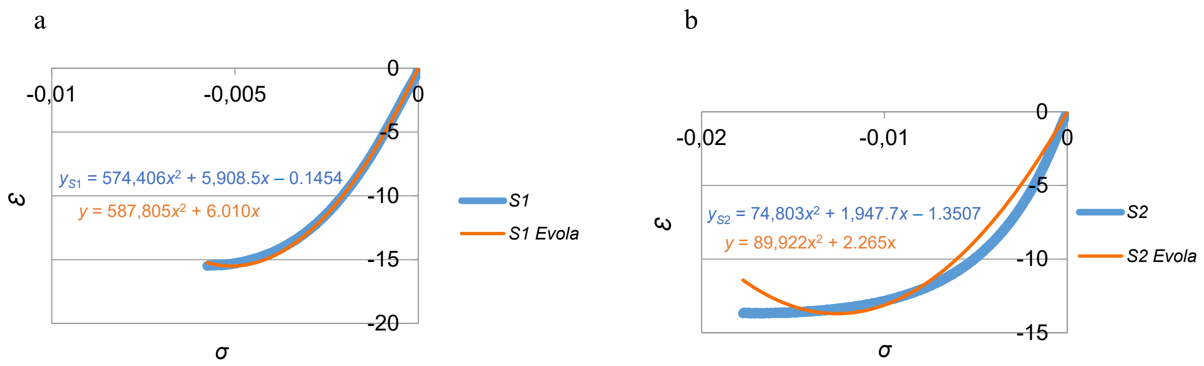

Fig. 6. Graphs of calculated functions *S*1 and *S*1 *Evola* (a) compared to functions *S*2 and *S*2 *Evola* (b)

Source: Karpiesiuk and Chyzy (2020).

Knowing the deformation and stress of the cement adhesives C2S1 and C2S2, these longitudinal elasticity modules were designated: *E*: E_{S1} equals 6,000 MPa and E_{S2} equals 2,300 MPa.

Poisson's ratio is the absolute value of the ratio of the transverse deformation to the corresponding axial deformation resulting from a uniformly distributed axial stress below the proportional limit of the material. It is described using following formula:

$$v = -\frac{\varepsilon_n}{\varepsilon_m}. \tag{5}$$

The coefficient *v* is estimated by conducting tests and subjecting it to a tensile or compressive force, according to the American standard ASTM E132-17 (ASTM International [ASTM], 2017), in the uniaxial state of stress. In the calculations, the arithmetic mean value of the Poisson's ratio in the elastic phase of the compressive stress of the cement adhesives from each sample was adopted, whose characteristics are close to linear and reach stable numerical values. Examples of the dependence of stress from the quotient of the ratio transverse to longitudinal deformation (*v*) C2S1 adhesive in tests with the extensometers are shown in Figure 7.

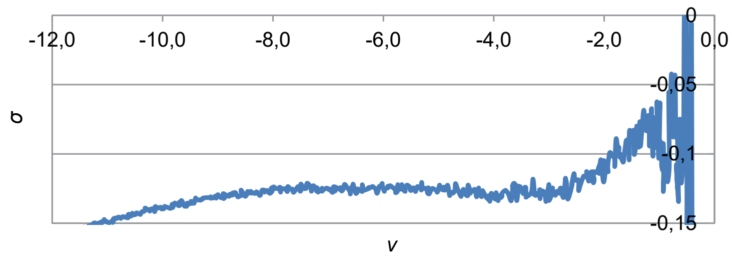

Fig. 7. The dependence of stress (σ) from the quotient of transverse to longitudinal deformation (v) in the cement adhesive C2S1

Source: own work.

Table 2 presents the longitudinal modulus of elasticity (E_{avg}) from a paper by Karpiesiuk and Chyzy (2020a), as well as the results of maximum compressive stresses and Poisson's ratio (v). Additionally, preliminary data of Young's modulus (E) for each type of adhesive are included, based solely on the experimental results without mathematical analyses. The full research and mathematical analysis are presented in the paper by Karpiesiuk and Chyzy (2020a).

Table 2. Deformable adhesives' mechanical characteristics

Adhesive	Averaged compression strength ($\sigma_{max\ avg}$) [MPa]	Averaged Young's modulus (E_{avg}) [MPa]	Averaged Poisson's ratio (v_{avg}) [-]
C2S1	15.52	5 900	0.13
C2S2	13.73	1 950	0.15

Source: own work.

The research of the thermal expansion (α_c) of C2S1 and C2S2 adhesives were carried out in a temperature range of 30–80°C. Underfloor heating is a low-temperature heating system; therefore, the sufficient maximum temperature measurement range is 50°C. However, for research purposes and the possibility of other applications of cement adhesives where the impact temperature difference is higher (e.g., terraces and balconies), the measurement range was increased to 80°C. The results of the coefficient α_c were determined from Eq. (6), found in standard ISO 527-2:2012 (ISO, 2012):

$$\alpha_c = \frac{\Delta L}{L_0 \cdot \Delta T}, \tag{6}$$

where:
α_c – thermal expansion [-],
ΔL – the length of the sample increase between the temperature intervals [mm],
L_0 – the length of the sample base at ambient temperature (20°C) [mm],
ΔT – temperature increase [°C].

The dependence of displacement (d_s) on research time (t) is shown in Figures 8 and 9 (C2S1 and C2S2 adhesives). The measurement base was 60 mm. The calculations were performed at temperature intervals of 10°C increments, from 30°C to 70°C. The two-colour differences, marked in Figures 8 and 9, show the two displacement results of three tested adhesive samples.

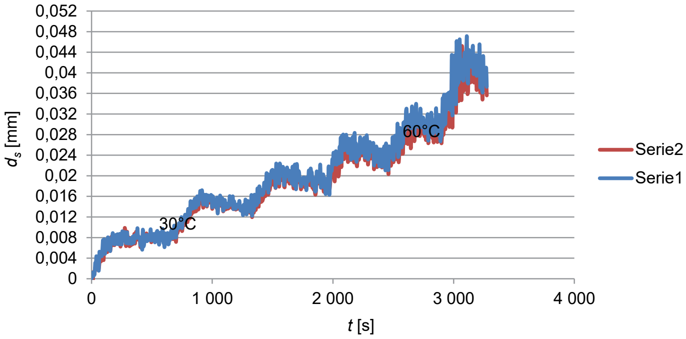

Fig. 8. The dependence of displacement (d_s) to time (t) for C2S1 adhesive samples

Source: own work.

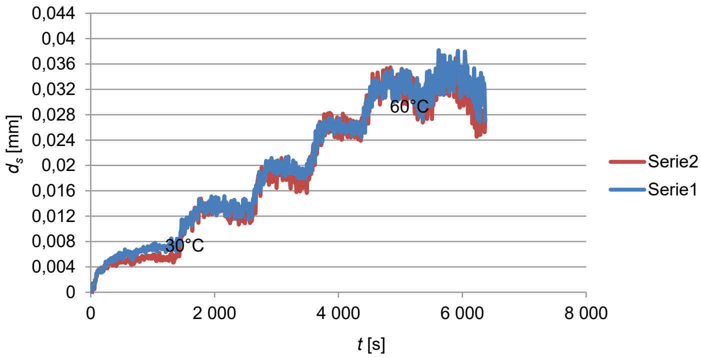

Fig. 9. The dependence of displacement (d_s) to time (t) for C2S2 adhesive samples

Source: own work.

Measurements verifying the thermal expansion coefficient (α) of cylindrical samples, performed at the Kraków University of Technology, in a temperature range 0–80°C of C2S1 and C2S2 adhesives, are shown in Figure 10. The calculation of the average values of the coefficient α was performed based on Eq. (6) and determined the subsequent trend lines (Fig. 10). The results summaries of rectangular and cylindrical samples of C2S1 and C2S2 adhesive are shown in Table 3.

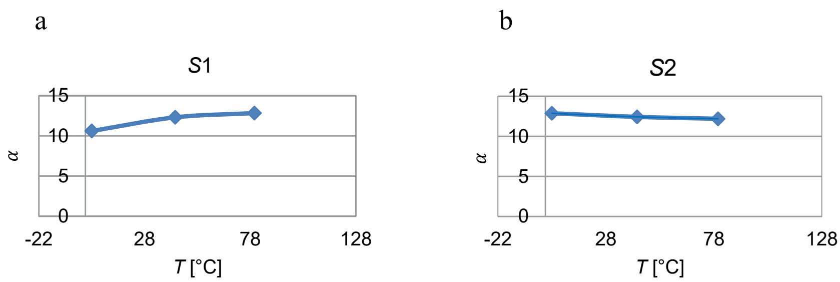

Fig. 10. Temperature (T) dependence on the coefficient of linear expansion (α) of C2S1 adhesive (a) and C2S2 adhesive (b)

Source: own work.

In this paper, material parameters such as Young's modulus (E), Poisson's number (ν) and thermal expansion coefficient (α) of deformable cement adhesives – C2S1 Sika Ceram 255 and C2S2 BASF Flex-mortar were determined. The C2S1 adhesive Young's modulus at the compressive strength test was 6,000 MPa, while the tensile strength was 5,950 MPa. For the coefficient α of two adhesives, on rectangular samples – using the DIC method and on cylindrical samples using an inductive sensor – the results were similar, considering the small value of α shown as 10^{-6} (Table 3).

Table 3. Average results of linear expansion coefficient ($\alpha_{c\ \mathrm{avg}}$) of C2S1 and C2S2 adhesive in Białystok and Kraków laboratories [$10^{-6} \cdot K^{-1}$]

Adhesive	Results from Białystok laboratory	Results from Kraków laboratory	Averaged results from both laboratories
C2S1	10.0	11.7	10.85
C2S2	13.0	13.6	13.30

Source: own work.

The standard EN 12004:2007+A1:2012 (CEN, 2007) gives many characteristics for cement adhesives used for tiles. Two of the most important adhesive characteristics are adhesion and deformability. The highest adhesion is marked in the standard with class C2, and deformability is marked with class S1 or S2. Class C2 means that the adhesion of the tested adhesive to a flat, even surface (e.g., concrete) must be either greater than or equal 1.0 $N \cdot mm^{-2}$. This adhesion value indicates the tensile strength perpendicular to the face of the adhesive mortar, attached to the substrate of the concrete slab according to the standard EN 1348:2007 (CEN, 2007). Classes S1 and S2 inform about the deformability of cement adhesives, where class S1 means deformable adhesives within 2.5–5 mm and class S2 indicates the highest deformability greater than 5 mm, according to standard EN 12002:2010 (CEN, 2010). Differences in the deformability of cement adhesives from 2.5–5 mm (i.e., up to 100%) allow manufacturers to produce them with higher or much lower quality. Similarly, adhesion, defined by the standard at a minimum of 1 MPa, allows the manufacturer to set the adhesion of the adhesive at a minimum value or well above the minimum value. The share of aggregate and cement in cement adhesives is approximately 90% (Leone, 2018), hence the value of adhesion and deformability is determined by various additives improving the "flexibility" and other features of cement adhesives. This means the client can find adhesives with the same marking but higher or lower quality for sale.

CONCLUSIONS

The strength parameters of cement adhesive types C2S1 and C2S2 were defined, such as Young's modulus (E), Poisson's ratio (ν) and the coefficient of linear thermal expansion (α). Many of the measurement techniques used allowed the verification of the obtained results. Additionally, the maximum compressive strength of deformable adhesives, longitudinal and transverse deformations were determined. This data can be used for the calculation of lightweight heated floor systems (LHFS) with a heating coil, as well as for all other building partitions such as balconies, patios, stairs and other horizontal or vertical surfaces on critical substrates, using one of the many numerical methods.

It is worth noting that deformable cement adhesives of C2S1 and C2S2 from specific manufacturers were tested. The standards EN 1348:2007 (CEN, 2007) and EN 12002:2010 (CEN, 2010) allow for significant discrepancies in the quality of these adhesives. For example, the deformation value in C2S1 adhesive may vary by up to 100% (permissible deformation is 2.5–5 mm). Therefore, the quality and material parameters of the same type of deformable adhesive from a different manufacturer may differ. Hence, it is worth repeating the tests using the same type of deformable adhesives but from other manufacturers. In this way, it is possible to check how big the differences, and whether they exist, are between strength material parameters E, v and α for many different manufacturers.

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NAJWAŻNIEJSZE WYTRZYMAŁOŚCIOWE PARAMETRY MATERIAŁOWE ODKSZTAŁCALNYCH KLEJÓW CEMENTOWYCH

STRESZCZENIE

Odkształcalne kleje cementowe typu C2S1 i C2S2 najczęściej są stosowane do klejenia płyt ceramicznych na tzw. podłożach krytycznych (innych niż beton), jak również w zmiennych warunkach atmosferycznych. Deklarowane wytrzymałości tych klejów mocowanych do podłoży betonowych można znaleźć w normach i deklaracjach producenta. Stosowanie klejów cementowych na powierzchniach innych niż beton lub w innych zastosowaniach, np. w systemie lekkiej podgrzewanej podłogi (LHFS), powinny spełniać normy bezpieczeństwa. Aby się o tym przekonać, należy ustalić podstawowe parametry wytrzymałościowe klejów odkształcalnych, które nie zostały dotychczas określone. W tym celu przeprowadzono wiele badań, m.in. wytrzymałości na rozciąganie i ściskanie, a także pomiar przemieszczeń w komorze termicznej, wykorzystując m.in. cyfrową korelację obrazu i techniki ekstensometryczne. Dzięki temu możliwe było określenie głównych parametrów wytrzymałościowych klejów odkształcalnych, takich jak: moduł Younga (E), współczynnik Poissona (v) oraz liniowy współczynnik rozszerzalności cieplnej (α). Te wielorakie techniki pomiarowe pozwoliły na uwiarygodnienie uzyskanych wyników, określenie maksymalnej wytrzymałości na ściskanie klejów odkształcalnych oraz odkształceń wzdłużnych i poprzecznych. Parametry materiału badawczego E, v i α można wykorzystać do obliczeń LHFS z wężownicą grzejną, a także dla innych przegród budowlanych lub na podłożach krytycznych (innych niż beton), wykorzystując niektóre z wielu metod numerycznych.

Słowa kluczowe: moduł Younga, współczynnik Poissona, współczynnik rozszerzalności cieplnej, odkształcalne kleje cementowe