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THERMAL ASPECTS OF FILLING GAPS AND LOSS IN CONCRETE PAVEMENT REPAIR

ASPEKT TERMICZNY WYPEŁNIANIA SZCZELIN I UBYTKÓW PRZY NAPRAWIE NAWIERZCHNI BETONOWYCH

Abstract

The paper summarizes the thermal aspect of bonding between engineering materials of different coefficients of thermal expansion. In such connections, there are thermal stresses generated. They may cause relevant decay of the mechanical properties of the bond under normal service temperatures. The experimental results show relevant influence of the temperature on bond performance, especially on durability of bonding in relation to the work under elevated variable temperature. The right selection of materials allows for increasing durability of connections. Mechanical properties of polyurethanes are stable in a wide temperature range over their glass transition temperature (occurring below -30°C), in opposite to epoxy resins, which glass transition temperature can be located in the range of environmental temperatures.

Keywords: durability, bonding, elevated temperature, adhesive layer

Streszczenie

W pracy przedstawiono zagadnienia połączeń materiałów konstrukcyjnych o różnych współczynnikach rozszerzalności termicznej. W przypadku takich połączeń generowane są naprężenia termiczne. Mogą one spowodować istotne zmiany właściwości mechanicznych połączenia w normalnych temperaturach pracy. Wyniki doświadczalne wykazują istotny wpływ temperatury na wytrzymałość połączenia, zwłaszcza w aspekcie jego pracy w zmiennych temperaturach. Odpowiedni dobór materiałów, pozwala na zwiększenie trwałości połączenia. Właściwości mechaniczne poliuretanów są stabilne w szerokim zakresie temperatur powyżej ich temperatury szklenia (występującej poniżej -30°C), co jest w opozycji do żywic epoksydowych, których temperatura szklenia może występować w zakresie temperatur środowiskowych

Słowa kluczowe: trwałość, klejenie, podwyższona temperatura, warstwa kleju

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Symbols

- Φ – diameter
- A – surface area
- l – length
- T – temperature
- T_g – glass transition temperature
- ρ – density
- α – thermal expansion coefficient
- σ – normal stress
- E – Young's modulus
- G – shear modulus

1. Introduction

Knowledge about the decrease of mechanical properties of bonding interface at elevated temperature is very limited and leads someone for better understanding, especially in the aspect of long term durability [1]. Epoxy resins, which are usually implemented in civil engineering constructions, change their mechanical properties above a glass transition temperature T_g , changing from a rigid material to a rubber like material. It was investigated by Leone et al. [2]. For epoxy adhesives, the shear stress distribution along the whole bond length represents exponential character with quick decaying. The effective bond length is

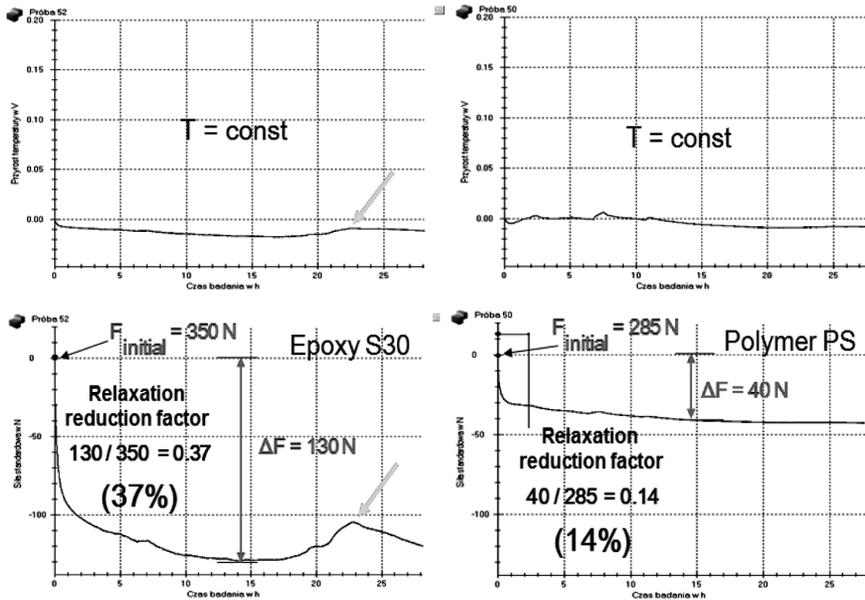


Fig. 1. Dynamic mechanical analysis (DMA) results obtained at the excitation frequency of 1 Hz for polyurethane PM – after [5]

also relatively low in the case of barely deformable and stiff interface materials [3]. In such cases, the bonding system is not fully exploited because of a low deformability interface. The same rules are also present for adhesives used in metal structures [4].

Epoxy resins, commonly using in strengthening systems, have limited exploitation temperature [5], because of their glass transition temperature (mostly $T_g = 35\div 70^\circ\text{C}$), thus covering fire protection is need. On the other hand, polyurethanes are almost stable at elevated temperatures up to 100°C (Fig. 1) [6], because their glass transition temperature is below the normal exploitation temperature range, thus allow for obtaining of better results in practical applications of civil engineering [7].

Advantageous mechanical properties of polyurethanes are due to their slightly larger ultimate deformations and the ability for decreasing of stress concentrations. The Flexible Joint Method, developed at the Cracow University of Technology, is based on polyurethane polymers using as adhesives layers in bonding of different engineering materials and FRP composites to concrete and masonry substrates [8].

Thermal stresses in a boundary area are depended on the coefficients of thermal expansion (CTE) and the Young modulus of an adhesive and of bonded materials. For materials with high value of Young's modulus, the change of a service temperature generates the significant stress increase and the cyclical circadian period has a great influence on durability of bonding. The knowledge of all parameters influencing the mechanical behaviour at the interface between different materials allows for an efficient numerical analysis [9] and designing [10].

2. Experimental

2.1. Measurement of the linear coefficient of thermal expansion

The coefficient of thermal expansion (CTE) was measured on cylindrical specimens of the diameter $\Phi = 28$ mm and the total length $L = 120$ mm. They were tested in a thermal chamber under stable temperature levels: room temperature (23°C), 40°C , 60°C , 80°C and 100°C for the period required to reach the stabilised elongation value ΔL . A displacement was measured using a WA-20 HBM Inductive Standard Displacement Transducer connected to a digital bridge QUANTUM MX840. The voltage temperature sensor was also connected to the bridge. The WA-20 transducer generated on sample the additional force equal $F = 1,2$ [N]. Coefficients of thermal expansion determined during the test for different materials are presented in Table 1 with their characteristics.

Table 1

Basic mechanical properties of presented polyurethanes determined during laboratory static tests at room temperature, according to ISO 527-1 [11]

Material	Young's modulus [MPa]	Tensile strength [MPa]	Elongation [%]	Coefficient of thermal expansion (CTE) [$10^{-6}/^\circ\text{C}$]
EPOXY S30	12800	28	0,22	30
PT	600	18	10	130
PS	8	2,2	45	158

Material	Young's modulus [MPa]	Tensile strength [MPa]	Elongation [%]	Coefficient of thermal expansion (CTE) [$10^{-6}/^{\circ}\text{C}$]
PST	6	2.5	110	140
PM	4	1.4	140	150
PSM	2.5	1.6	150	169

2.2. Measurement of basic mechanical properties

Basic mechanical properties in tension and compression were measured at room temperature according to EN ISO 527-1 [11], using an universal testing machine ZWICK 1455 and a digital extensometer. The obtained results for the tested materials are presented in Table 1.

2.3. Measurement in the absence of the deformation possibility

The basic experiment carried out for epoxy and polymer PS cylindrical samples, with the diameter of $\Phi = 28$ mm and the total length $L = 120$ mm, consisted of two parts. The first one was performed at the constant room temperature (23°C) with the constant initial load of 350 N for epoxy and of 285 N for polymer PS, generated by the universal testing machine. During the test, the traverse position was locked and relaxation was measuring for 28 hours. The obtained results are presented in Fig. 2.

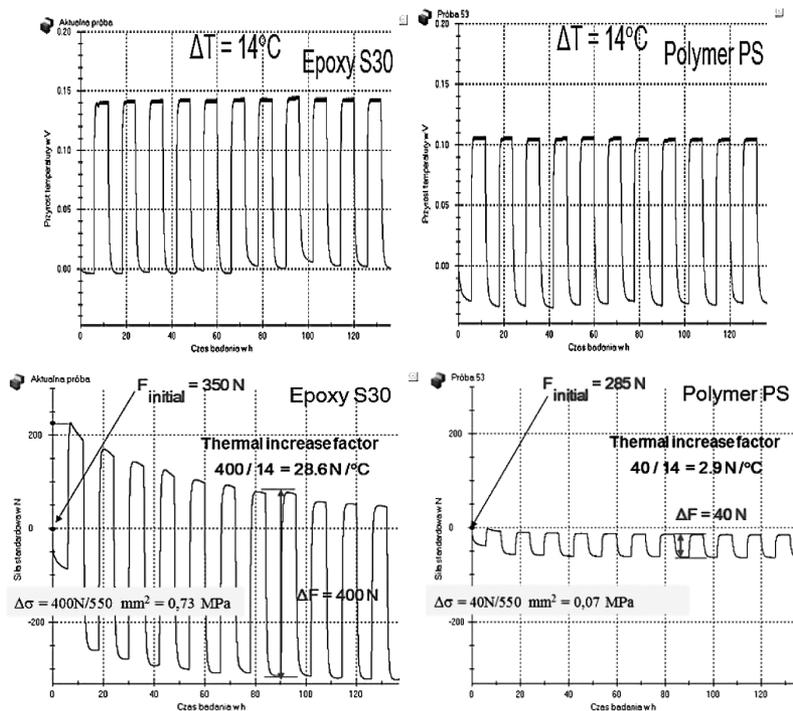


Fig. 2. The behavior of the material in the gap with the absence of the possibility of deformation

The great amount of the relaxation force decrease was observed during the first hour and then was started to be stable. After 15 hours, the drop of force for epoxy was 130 N (37% of the initial value) and for polymer PS was 40 N (14% of initial value). The epoxy material sample was very sensitive to temperature changes. It was observed during the test that a slight increase of the room temperature generated increase of the stress in the specimen (green arrow in Fig. 2).

The second part of the experiment was developed in the temperature chamber. The specimens of the same size (like in the first part) were investigated in the same way as previously – the constant initial load of 350 N for epoxy and 285 N for polymer PS and with the locked testing machine position. The samples were alternately heated and cooled in cycles of temperature level changing from room temperature (23°C) to 37°C (increase of $\Delta T = 14^\circ\text{C}$). The duration of each cycle was six hours and the whole test was 130 hours. Changes of temperature and of the force generated by the thermally working epoxy and polymer PS specimens are presented in Fig. 3.

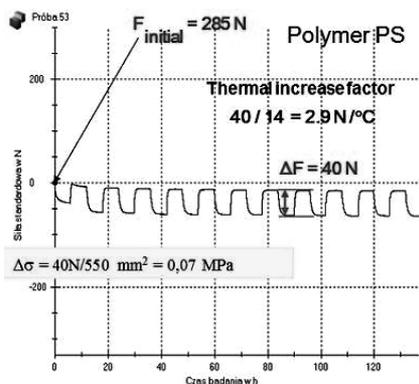


Fig. 3. Change of the force generated by temperature cycles: $\Delta T = 14^\circ\text{C}$; in 6 hours intervals with blocking of the specimen thermal elongation

The presented results indicate that epoxy resin generates 10 times higher level of the force (and stress in a real structure) than polymer PS under changes of temperature. The level of the additional stress forced by epoxy under the temperature increase of $\Delta T = 14^\circ\text{C}$ is equal to 0.73 MPa. It is a quite huge value in comparison to the tensile strength of the low strength concrete ($f_{\text{ctk},0.05} = 1.3 \text{ MPa}$ for C16/20) especially, when the temperature increase is double (the real temperature increase value in winter-summer season cycles). Such material, filling gaps (cracks) in a concrete structure, can cause additional damages initiated by thermal stress. On the other hand, polymer PS applied in a cracked structure will not generate such dangerous level of thermal stress. It has to be mentioned that the specimens of the cylindrical shape were constrained only in the direction of the uniaxial test with possibility of free deformation around cylinders. It is not typical for the real application, thus the obtained stress level is lower than expected in real cracks, where filling material is constrained around its volume.

2.4. Thermal stress factor

The thermal stress factor described by equation 1 is a measure allowing compared deformation of various materials under temperature changes, which is especially important in the case of a stiff bond joining different engineering materials. Temperature changes are responsible for the formation of thermal stress and they have a great influence for durability of the bond of materials of different CTE for long time period. Such effect is important not only in the situation of filling gaps (cracks) but also for the surface repair, where covering of old structure with new repair material exist. A better way of bonding in such conditions is using materials with similar CTE for stiff connections or using the highly deformable material (e.g. polyurethanes), generating low thermal stress as the interface between joined materials of the different thermal behaviour. The highly deformable material will compensate difference in elongation of materials with different CTE in bonding area and will not generate high amount of thermal stress.

$$E\alpha = \frac{\Delta\sigma}{\Delta T} \quad (1)$$

where:

- E – Young's modulus [N/mm²],
- α – thermal expansion coefficient [1/°C],
- $\Delta\sigma$ – change of stress [N/mm²],
- ΔT – change of temperature [°C].

Comparison of crucial parameters for two epoxy resins and five polyurethanes is presented in Fig. 4 and Fig. 5. The thermal stress factor is an indicator of the thermal stress level, which can be used in the choosing of proper material for the interface construction.

The polymer PS has a very low thermal stress factor in comparison to other engineering materials, as described in Fig. 6. Materials of the high Young's modulus have significantly higher value of the thermal stress factor in comparison to polyurethanes. They can generate the high level of thermal stress in a bond under normal exploitation temperatures. The calculated thermal stress values, for the increase of the service temperature of about 30°C, are presented in Fig. 7, using the thermal stress factors from Fig. 6. It is obvious that lack of free deformation possibility generates quite huge level of thermal stress in stiff materials.

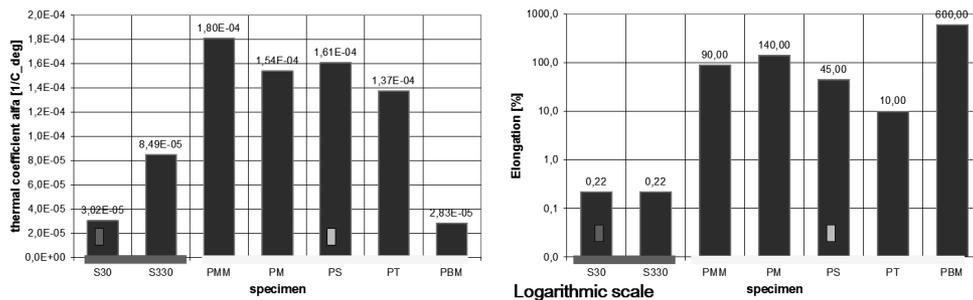


Fig. 4. Comparison of thermal coefficients of expansion and ultimate elongations of epoxy resins and polyurethanes (in logarithmic scale)

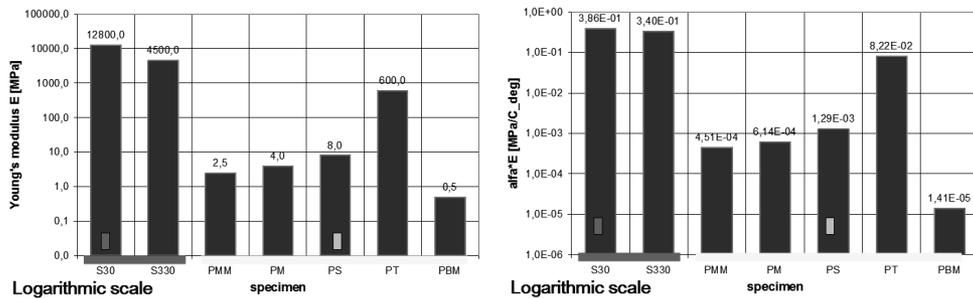


Fig. 5. Comparison of stiffness module (E) and thermal stress factors ($E \cdot \alpha$) of epoxy resins and polyurethanes (in logarithmic scale)

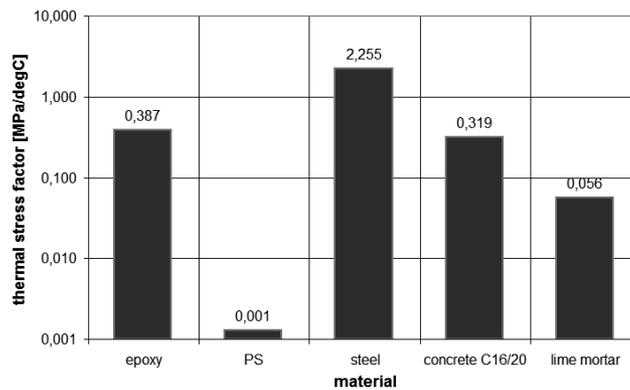


Fig. 6. Distribution of the thermal stress factor ($E \cdot \alpha$) per 1°C in logarithmic scale

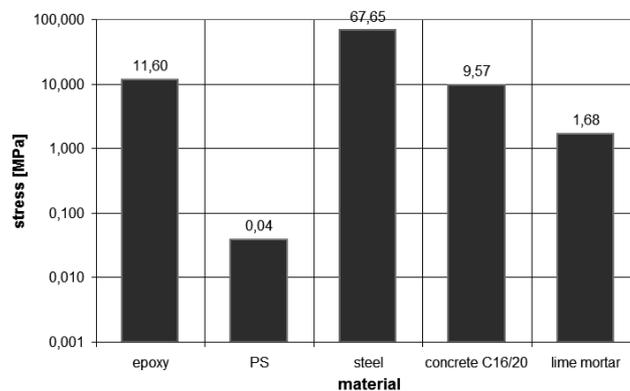


Fig. 7. Thermal stress ($\Delta \sigma$) calculated for 30°C change in logarithmic scale

In real applications, the most important aspect is the difference in stress between joined materials, responsible for the generating of shear stress in the interface.

For a stiff connection between an old concrete (e.g. C16/20) and a repair epoxy cover (e.g. S30), the calculated difference in stress is about 2 MPa under the temperature increase of 30°C (Fig. 7). Such high level of stress is responsible for the detachment of epoxy cover, observed in an engineering practice. A typical failure mode is cohesive detachment in concrete. It is also caused by the influence of low deformability of the joined materials (the ultimate elongation of concrete is about 0.2% and of epoxy is up to 2%). If the polymer PS is applied as a filament of gaps or a cover of concrete, it does not generate the high stress level and additionally its high deformability (the ultimate elongation of polymer PS is about 45%) protects such flexible cover against detachment. This aspect is also advantage in the case of the long time durability behaviour.

3. Conclusions

The study showed that:

- the epoxy resin S30 has the coefficient of thermal expansion of about 3 times higher than concrete, while polymer PS has it about 15 times higher;
- at the service temperature range of $-20\div 70^{\circ}\text{C}$, polyurethanes operate above their glass transition temperature, while epoxy resins operate generally below their glass transition temperature, but they may achieve this temperature even in the temperature range of $35\div 65^{\circ}\text{C}$;
- the relaxation value of the epoxy resin S30 is more than twice of the polyurethane PS;
- the change in temperature results in higher stress magnitude in the case of the epoxy S30 than in the case of the polymer PS;
- for the thermal analysis, it is essential to fill a crack with the material of the low thermal stress factor, expressed by the Young's modulus multiplied by the coefficient of thermal elongation ($E\alpha$);
- the epoxy S30 has the thermal stress factor 300 times higher than the polymer PS;
- repairing cracked structure subjected to a large temperature gradient, it is more appropriate to use the polymer PS as it generates lower stress than the epoxy S30;
- applying of the flexible bonding is more advantageous than the stiff one, if a structure is subjected to thermal influences;

Symbols: **PS**, **PT**, **PM**, **PSM**, **PST** (and others, not mentioned in this paper) are names of two component polyurethanes applied in the Flexible Joint Method, developed in the Institute of Structural Mechanics of the Cracow University of Technology. Various applied in civil engineering technologies based on the Flexible Joint Method are protected by patents PL207028 (B1), PL214295 (B1) and PL215827 (B1).

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