Budownictwo i Architektura 24(2) 2025, 21-32

DOI: 10.35784/bud-arch.6866
Received: 28.11.2024; Revised: 05.12.2024;
Accepted: 09.12.2024; Available online: 25.06.2025

Crossref Similarity Check Powered by iThenticate

Orginal Article

Adhesion analysis between geopolymer and mineral-asphalt composite

Krzysztof Granatyr

Faculty of Civil and Environmental Engineering; Bialystok University of Technology; ul. Wiejska 45 E, 15-351 Bialystok, Poland; krzysztof.granatyr@pb.edu.pl; ORCID: 0009-0001-6763-1742

Abstract: The article presents research on the influence of the variable composition of geopolymer concrete on its ability to bond with asphalt concrete. The experimental variables included the proportion of mortar in the geopolymer concrete, the molarity of NaOH in the activator, and the thickness of the geopolymer layer in the road composite. The curing conditions remained constant. Tests were conducted to evaluate interlayer adhesion using the Leutner method, as well as compressive strength, shrinkage, and temperature deformation. The obtained results confirm the interlayer bonding values in each tested case. The interlayer adhesion test was performed according to a three-factor experimental design at three levels of variability. The factors considered were: geopolymer layer thickness (15, 30, 45 mm), molar concentration of NaOH in the activator (8, 10, 12 mol/L), and mortar content in geopolymer concrete (45%, 55%, 65%). All factors significantly influenced interlayer adhesion. The shrinkage of the geopolymer and mineral-asphalt composite was lower than that of geopolymer concrete. Additionally, deformation at both low and high temperatures was lower in the geopolymer and mineral-asphalt composite.

Keywords: geopolymer and asphalt composites, interlayer adhesion, thin protective layers

1. Introduction

This article presents a study on the effects of varying geopolymer concrete compositions on its ability to bond with asphalt concrete [1]. Pavement construction layers, such as the wearing course, binder course, and substructure, are mostly composed of mineral-asphalt mixtures. While asphalt road pavements offer several advantages, including resistance to dynamic loads, good adhesion to vehicle tyres, and the possibility of rapid rehabilitation, they also have significant drawbacks: sensitivity to extreme temperatures, a dark colour requiring more energy for lighting, higher construction costs compared to concrete pavements, and high maintenance and repair costs [3].

The wearing course of an asphalt road pavement, which is in direct contact with vehicle wheels, is particularly susceptible to atmospheric conditions and temperature fluctuations. These factors can lead to deformation and mechanical damage, especially during the winter-spring period [1]. Despite the use of various materials for the construction of the wearing course – such as grit mastic, poured asphalt, asphalt concrete for very thin layers, or porous asphalt – the service life of this layer remains limited under the climatic conditions found in Poland [2,3].

The geopolymer concrete proposed in this article for a thin protective-wearing layer demonstrates significantly better properties than traditional cement or asphalt concretes [4]. It exhibits high compressive and flexural strength, with a flexural-to-compressive strength ratio of approximately 4.5:10. Additionally, it offers excellent weather resistance, as well as resistance to chloride, sulfate, and acids. It also possesses high thermal resistance to both low and high temperatures (ranging from -40°C to approximately +900°C), exceptional frost resistance, strong adhesion to various materials, and no shrinkage during setting, ensuring dimensional stability [4]. A key advantage of geopolymers is their ability to utilise combustion by-products, such as fly ash or blast furnace slag from industrial sources, as the primary binder, eliminating the need for Portland cement [5].

Previous research has mainly analysed shear stress values in homogeneous materials, such as cement concrete or geopolymer concrete [6,7]. However, shear stresses occurring between two materials with different properties have been less frequently studied [8]. The author of this paper has conducted, for the first time, interlaminar grafting tests on geopolymer concrete and asphalt concrete. In previous studies, shear strength assessments – including both reinforced and unreinforced composite materials – relied on different methodologies and equipment [7,9,10]. In the case of cementitious concretes, numerous studies have explored theoretical and empirical relationships between shear stress values and factors such as compressive strength, apparent density, reinforcement presence, construction type, and the roughness of the bonded materials [7].

This article presents the results of a study on the adhesion of geopolymer thin layers to asphalt concrete, which is the key parameter determining the durability of the geopolymer-asphalt concrete bond and, consequently, the interlayer performance of these materials [9].

2. Materials and methods

The experiment was designed to investigate the interlayer bondability of geopolymer concrete and asphalt concrete. A three-factor test plan was developed with three levels of variation, where X_1 represents the molar concentration of NaOH in the activator [mol/dm^3], X_2 denotes the thickness of the geopolymer concrete layer [mm], and X_3 corresponds to the percentage of mortar in the geopolymer concrete [%]. Details of the test plan, including coded and actual values, are provided in Tab. 1.

Table 1. Experimental plan. *Source*: own study

Series	Real values		
Nr	X_1 – molarity of NaOH in the activator [mol]/l	X_2 – thickness of the geopolymer concrete layer [mm]	X_3 – mortar content in geopolymer concrete [%]
1	8	15	45
2	12	15	45
3	8	45	45
4	12	45	45
5	8	15	65
6	12	15	65
7	8	45	65
8	12	45	65
9	8	30	55
10	12	30	55
11	10	15	55
12	10	45	55
13	10	30	45
14	10	30	65

The geopolymer concrete was designed based on generally accepted principles for the design of rolled concretes, including consideration of US guidelines [11]. The composition was modified by adjusting the percentage of mortar in the mix volume while maintaining a constant amount of grout, which was altered by varying the concentration of sodium hydroxide. The wearing layer of the geopolymer concrete was produced using natural sand (0–2 mm fraction), basalt aggregate (2–5 mm fraction), and melaphyre aggregate (11–16 mm fraction). Three different concentrations of NaOH solution were used in the tests: 8, 10, and 12 mol/dm^3, along with sodium water glass (Na_2SiO_3). The Na_2SiO_3/NaOH ratio was 2.5. Three different aggregate mixtures were prepared for the analyses, featuring varying grain distributions and sand points. A fraction with a grain size of 0–2 mm and a geopolymer slurry with a fixed composition resulted in mortar contents of 45%, 55%, and 65% in the mix volume. The initial composition of the geopolymer concrete is shown in Tab. 2.

Table 2. Basic mix design of geopolymer concrete. *Source*: own study

Component	Quantity per 1 m^3 [kg]
Sand 0-2	725
Basalt 2-5	327
Basalt 5-8	368
Melaphyre 8-11	397
Fly ash Ostroleka	400
Activator 12M	200

Fly ash from the combustion of hard coal dust at the Ostrołęka Combined Heat and Power Plant was used in the study. The oxide composition of the fly ash is presented in

Table 3. The fly ash has a specific density of 2.23 g/cm³, a bulk density of 1.15 g/cm³, a specific surface area of 3,700 cm²/g according to the Blaine method, and a loss on ignition of 4.37%. According to PN-EN 450, it qualifies as category A fly ash [12].

Table 3. Chemical composition of fly ash. *Source*: own study

Parameter under study	Result (% by weight)
SiO_2	54.6
Fe_2O_3	4.97
Al_2O_3	25.30
TiO_2	1.07
CaO	2.14
MgO	1.80
SO_3	0.37
Na_2O	0.84
K_2O	2.80
Loss of Ignition	4.37

Asphalt concrete designated as AC16W35/55 was developed for the study, meeting the requirements of the General Directorate for National Roads and Motorways [13] for binder courses in traffic categories KR3–KR5. The concrete mix design was carried out using the MASA computer program. The mineral-asphalt mixture consisted of crushed gravel aggregate and filler in the form of lime meal. Road asphalt 35/50 was used to prepare the mineral-asphalt mixture, which is commonly applied in road base and binder layers for traffic categories KR3–KR7. The composition of the asphalt concrete is presented in Tab. 4.

Table 4. Composition of asphalt concrete. *Source*: own study

Asphalt concrete	Percentage proportion
Limestone powder	4.77
0-2 natural sand	17.17
2-5 natural crushed gravel	24.8
5-11 natural crushed gravel	20.03
11-16 natural crushed gravel	28.62
Bitumen 35/50	4.6

2.1. Interlaminar bonding test

The test was conducted on 14 series of cylindrical specimens with a diameter of 100 mm and varying wearing course heights: 15 mm, 30 mm, and 45 mm. The asphalt concrete layer had a fixed height of 70 mm. The compositions of the different mixes varied in the molar concentration of sodium hydroxide in the activator (8 mol/dm³, 10 mol/dm³, 12 mol/dm³) and the percentage of mortar in the geopolymer concrete, which was 45%, 55%, and 65%, respectively. The cylindrical samples were prepared using a laboratory mixer, followed by compaction in a gyratory press in accordance with EN 12697-31 [14]. The cylindrical moulds were preheated to 140°C and then coated on the inside with a thin layer of glycerine. The layers of both concrete types were compacted in fifty cycles, after which the moulds containing the composite were placed in sealed plastic string bags and stored in a laboratory dryer heated to 90°C. The dryer was then switched off, allowing for spontaneous cooling, simulating the pavement maturation process under road pavement implementation conditions. Figure 1 presents a graph depicting the temperature drop in the road composite and the interior of the dryer.

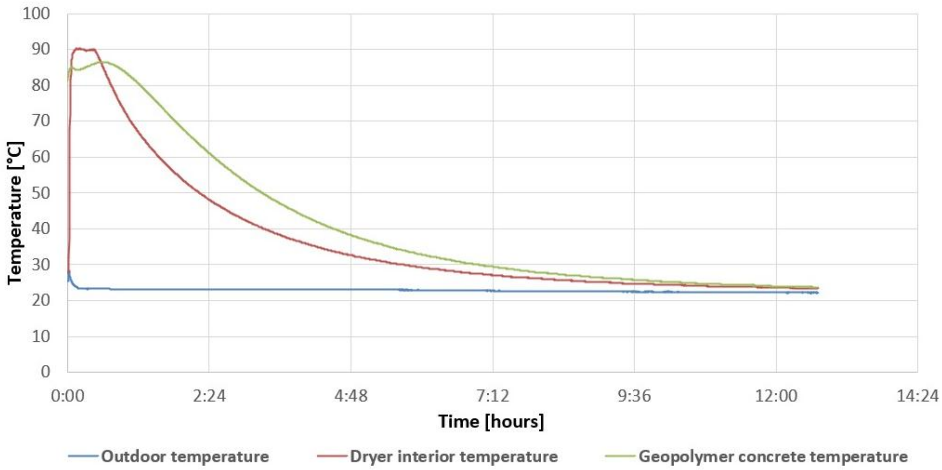

Fig. 1. Diagram of the temperature drop in the road composite under simulated conditions. *Source*: own study

After the maturation period, the road composite was placed in a Leutner apparatus to test the interlaminar bonding of the two constituent materials. The shearing process commenced at a piston travel speed of 50 mm/min ± 3 mm/min and continued until the maximum force, or shear failure point, of the sample was reached [15].

2.2. Compressive strength test

The modified test plan for compressive strength was developed by removing the variable "thickness of the geopolymer concrete layer," resulting in a two-factor test plan with three levels of variation, yielding eight test series. The preparation of the geopolymer concrete was carried out in a mixer, and the mixture was subsequently compacted in preheated 100 mm steel moulds at 90°C. Vibration was applied in two phases using a vibrating machine: the first phase involved compacting the mixture for 30 seconds using a bottom vibrator, while the second phase lasted 90 seconds and employed a top press. Finally, all moulds were placed in a laboratory dryer heated to 90°C, which, together with the samples, was left to cool naturally. Compressive strength testing was conducted according to PE-EN 12390-3 [16] after 28 days of curing.

2.3. Shrinkage test

Shrinkage testing using the Amsler method was performed in accordance with PN-84/B-06714/23 [17] on specimens measuring 100 × 100 × 500 mm. Shrinkage was measured after 24 hours, and at 3, 7, 14, 28, and 90 days of geopolymer concrete curing. The specimens were compacted with a vibratory hammer in compliance with EN 13286-51 [18]. After compaction, both the geopolymer concrete and road composite samples were placed in a laboratory dryer and heated to 90°C for 24 hours.

3. Research results and analysis

3.1. Interlayer bonding test

Table 5. Average shear stress results for the test series. *Source*: own study

Series	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average value [MPa]	1.7	1.6	1.5	1.6	2.6	1.8	1.8	2.1	2.1	1.6	2.2	1.9	1.9	2.0

The average shear stress results are presented in Tab. 5. Statistical analysis indicates that the molar concentration of NaOH (x) in the activator, the percentage of mortar, and the layer thickness had a significant effect on shear stress, with a significance level of $\alpha = 0.05$.

$$\hat{y} = 1.087749 - 0.06x_2 + 0.057686x_3 + 0.005376x_1x_2 - 0.003892x_1x_3 \quad (1)$$

$$R^2 = 0.6272$$

The relationship between shear stress and the molar concentration of NaOH in the activator, as well as the thickness of the geopolymer layer, is presented in Fig. 2. The correlations between shear stress, the molar concentration of NaOH in the activator, and the mortar content of the geopolymer concrete are shown in Fig. 3.

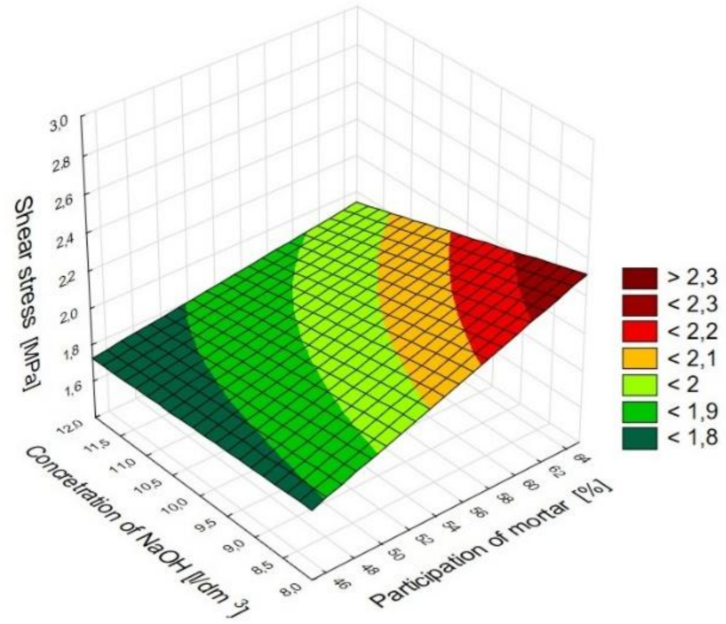

Fig. 2. Correlation of shear stress with NaOH concentration and mortar content in geopolymer concrete after 28 days of curing. *Source*: own study

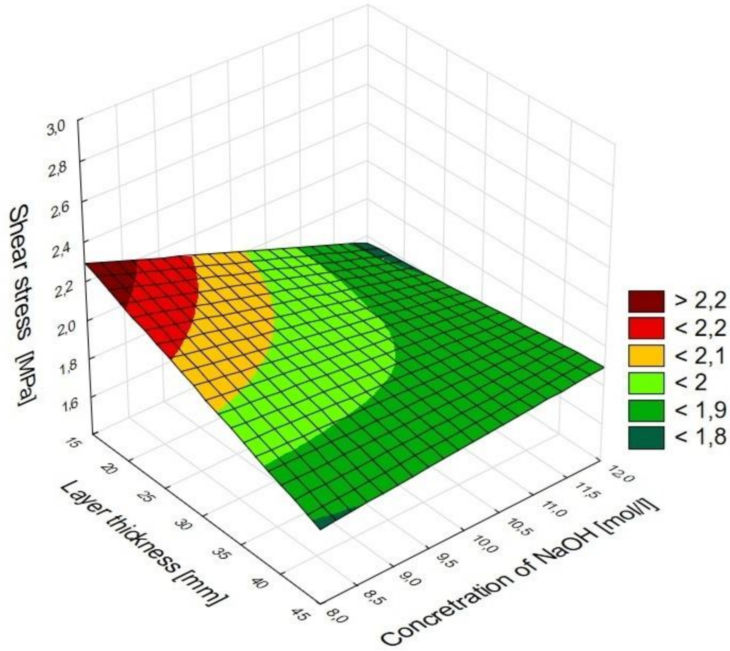

Fig. 3. Correlation of shear stress with NaOH concentration and geopolymer concrete layer thickness after 28 days of curing. *Source*: own study

The results obtained indicate a direct proportionality between the increase in shear stress and the concentration of NaOH in the activator for a 45% mortar content in geopolymer concrete, which aligns with the trend observed in Fig. 2. This finding confirms expectations based on available literature [9], which suggests a similar relationship for the compressive strength of geopolymers. However, for mortar contents of 55% and 65% in the geopolymer concrete, an inverse relationship was observed with respect to NaOH concentration in the activator. The highest shear stress values were recorded for an 8 molar NaOH concentration and a 65% mortar content in the geopolymer concrete.

A similar trend is observed when analyzing the effect of geopolymer concrete layer thickness on interlayer bonding. For a layer thickness of 45 mm, the bonding values increase with increasing NaOH concentration in the activator. However, for layer thicknesses of 30 mm and 15 mm, the bonding values increase as NaOH concentration decreases. This effect can be attributed to the higher content of fine fractions in the geopolymer concrete mix and the improved plasticity achieved with an 8 molar NaOH solution, which enhances the interface development with the asphalt concrete layer. Additionally, a thinner geopolymer concrete layer allows for more effective compaction with greater energy.

3.2. Compressive strength test

Table 6. Average compressive strength results for the test series. *Source*: own study

Series	1	2	3	4	5	6	7	8
Compressive strength [MPa]	16.0	26.4	29.2	31.4	29.3	46.7	23.6	32.1

The average compressive strength results are presented in Tab. 6. The compressive strength values obtained after 28 days of curing confirm the high strength of geopolymer concrete. The highest results were recorded for the formulation containing a 12 molar NaOH concentration in the activator and a 55% mortar proportion in the mix, where the maximum strength exceeded 45 MPa. Conversely, the lowest compressive strength values were observed for concrete produced with an 8 molar NaOH concentration and a 55% mortar content. Analysis of the corresponding graph (Fig. 4) indicates that the most favourable composition includes a 55% mortar content. This result was expected, as the mix design was developed in accordance with American guidelines for rolled concretes.

The high compressive strength values obtained for formulations containing a 12 molar NaOH activator confirm consistency with previous research findings available in the literature [4].

$$\hat{y} = -445.07 + 10.789x_1 + 14.773x_2 - 0.157x_1x_2 - 0.116x_2^2 \quad (2)$$

$$R^2 = 0.8098$$

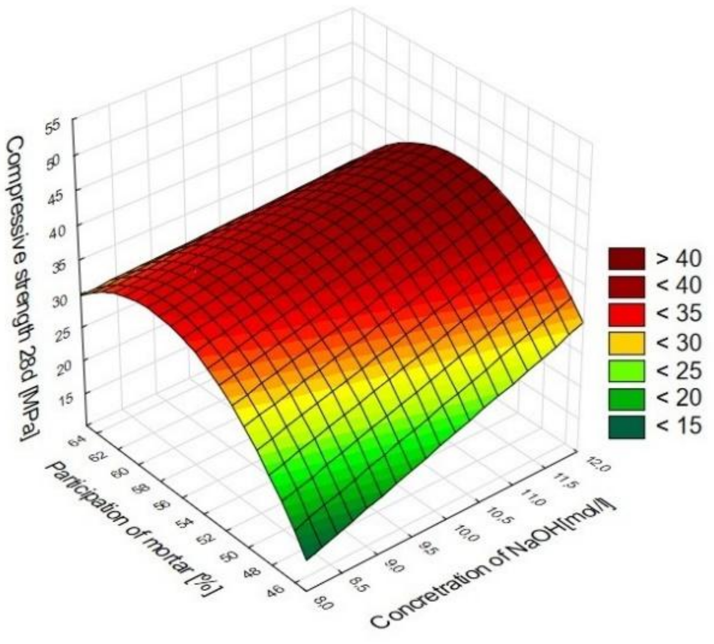

Fig. 4. Correlation of compressive strength with NaOH concentration and mortar content in geopolymer concrete after 28 days of curing. *Source*: own study

3.3. Shrinkage test

The geopolymer concrete and road composite mixtures were tested for shrinkage strain. Shrinkage was measured after 3, 7, 28, 60, and 90 days, with the measurement taken after 1 day considered as the baseline (point 0), following the procedure described in section 2.3.

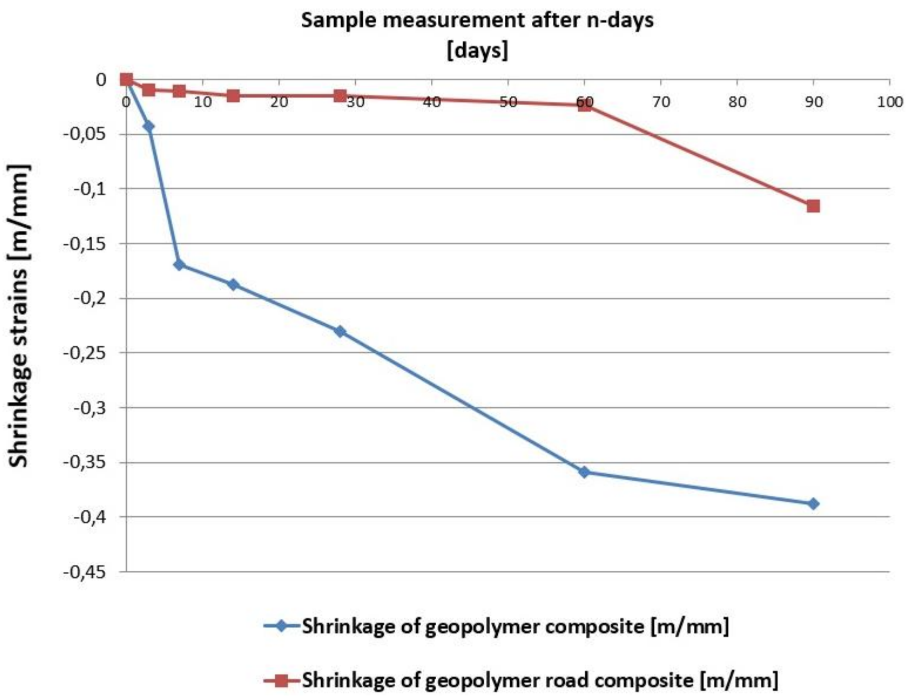

Fig. 5. Shrinkage results of geopolymer concrete and road composite. *Source*: own study

The most significant increase in volume change for geopolymer concrete was observed during the first seven days of curing, while the smallest increase occurred between 60 and 90 days, indicating a stabilization of the results. Over a 28-day maturation period, the shrinkage values remained similar; however, after 90 days, the shrinkage values of fibre-reinforced concrete were approximately 15% lower and, compared to unreinforced concrete, up to 35% lower [19].

The shrinkage values of the road composite were an order of magnitude lower than those of the geopolymer concrete. A minimal increase in shrinkage strain was observed over 60 days, with a slight increase between 60 and 90 days of curing. The study suggests that the asphalt concrete binder course largely compensates for the shrinkage strain of the geopolymer concrete used as the wearing course.

Additionally, thermal expansion tests were conducted. The road composite and geopolymer concrete beams were tested in an Amsler apparatus at 20°C, then cooled to -30°C and retested. The second phase involved reconditioning the beams to 20°C, followed by placement in a laboratory dryer for 24 hours at 65°C, after which the temperature deformation was measured. The results obtained are presented in Fig. 6.

By comparing the graphs, it can be observed that the road composite exhibits only slightly greater deformation at -35°C than geopolymer concrete alone, despite the presence of asphalt concrete as the binder course. At 65°C, the dimensional change of the road composite, compared to geopolymer concrete, was reduced to nearly zero. These findings suggest that the combination of asphalt concrete and geopolymer concrete within the road composite balances their respective properties. This results in a reduction in the low-temperature deformation typically observed in mineral-asphalt mixtures, as well as a decrease in the linear thermal expansion of geopolymer concrete.

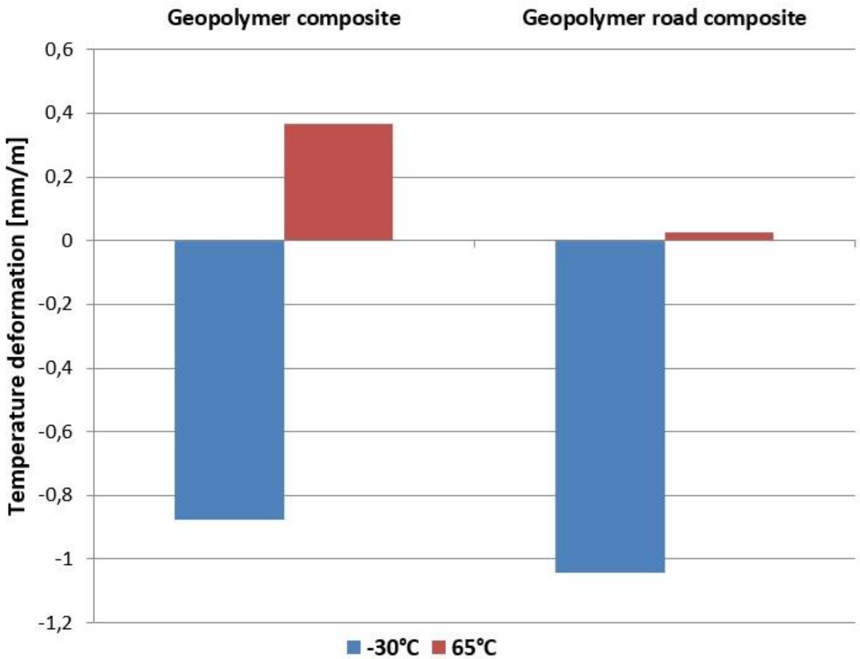

Fig. 6. Temperature deformation of the road composite and geopolymer concrete. *Source*: own study

Based on the results obtained, the coefficient of linear thermal expansion (α) was calculated for the tested materials over the specified temperature range using formula (1).

$$\alpha = \frac{\Delta l}{l_0 \Delta T} \tag{3}$$

The calculated coefficients of linear thermal expansion are presented in Table 7.

Table 7. Calculated coefficients of linear thermal expansion. *Source*: own study

Material	Coefficient of linear thermal expansion [10-6 /K]	
	-30°C - 20°C	20°C - 65°C
Geopolymer concrete	17.5	8.1
Road composite	20.8	0.6

Based on the results obtained, it was observed that geopolymer concrete, in the temperature range of 20°C – 60°C, has a lower coefficient of linear expansion than cement concrete [20]. Additionally, the road composite does not exhibit linear thermal deformation, which is a crucial factor in the design of road pavements.

4. Summary

Studies on the adhesion of geopolymer concrete to asphalt concrete highlight the significance of factors such as the molar concentration of NaOH, the thickness of the geopolymer layer, and the proportion of mortar. The optimal conditions were determined to be 8 mol NaOH, a 45% mortar proportion, and an appropriate layer thickness. Geopolymer concrete demonstrates high strength, particularly in formulations with 12 mol NaOH and a 55% mortar proportion. The application of these composites in road pavements appears promising, particularly in compensating for differences in thermal expansion. Further research is necessary to deepen the understanding of these factors and integrate them into practical applications. The study presented here is part of a broader investigation into the use of UPS in the production of construction materials with diverse properties, including high-quality, durable pavements.

References

[1] *Diagnosis of the condition of the pavement and selected elements of the road body – application guidelines, Appendix L1: Catalogue of defects in the system of automatic evaluation of asphalt pavements*, GDDKiA, 2019.

[2] Amini B., Tehrani S., "Simultaneous effects of salted water and water flow on asphalt concrete pavement deterioration under freeze-thaw cycles", *International Journal of Pavement Engineering*, vol. 15(5), (2012), 1-9. https://doi.org/10.1080/10298436.2012.677844

[3] Blażejowski K, Wójcik-Wiśniewska M. Baranowska W, "Asphalts in Polish climatic conditions, Asphalt Surfaces", *Nawierzchnie Asfaltowe*, vol. 3(51), (2017), 6-12 (in polish). http://www.nawierzchnieasfaltowe.pl/wp-content/uploads/NA_PSWNA_351_2017.pdf

[4] Mikuła J. eds., *Pro-ecological solutions in the production of Modern environmentally friendly composite materials*, Wydawnictwo PK, Cracow, 2014.

[5] Kalinowska-Wichrowska K, Gosk E, Rakowski B, Chuczun A, "Basic properties of geopolymers with addition of ceramic waste", *Building Materials*, vol. 8, (2022), 80-83. https://doi.org/10.15199/33.2022.08.14

[6] Boltryk M., Stankiewicz N., "Thin protective layers made out of special concretes", *Solid State Phenomena*, vol. 259, (2017), 101-105. https://doi.org/10.4028/www.scientific.net/SSP.259.101

[7] Yacob N. S., El Gawady M. A., Sneed L. H., Said A., "Shear strength of fly ash-based geopolymer reinforced concrete beams", *Engineering Structures*, vol. 196, (2019), 1-12. https://doi.org/10.1016/j.engstruct.2019.109298

[8] Boltryk M., Granatyr K., Stankiewicz N., "Ecological aspects in the aplication from geopolymer composites on road surfaces", *Economics and Environment*, vol. 68(1), (2019), 193-202. https://doi.org/10.34659/kepq-z363

[9] Jaskuła P., *Adhesion of asphalt layers in multilayer road pavement systems*, Gdańsk University of Technology Publishing House, Gdańsk, 2018.

[10] Wu C., Hwang C., Shi C., Li, N. Du Y., "Shear tests on reinforced slag-based geopolymer concrete beams with transverse reinforcement", *Engineering Structures*, vol. 219, (2020), 1-13. https://doi.org/10.1016/j.engstruct.2020.110966

[11] *Guide for roller-compacted concrete pavements*, National Concrete Pavement Technology Center at Iowa State, University's Institute for Transportation, funding from Portland Cement Association, August 2010.

[12] *PN-EN 450-1:2012 Fly ash for concrete - Part 1: Definitions, specifications and conformity criteria*, PKN, Warsaw, Poland, 2012.

[13] *WT-2 2014 - Part I Mineral and bituminous mixtures. Technical requirements*, GDDKiA, 2014.

[14] *PN-EN 12697-31:2019-03 bituminous mixtures - Test methods - Part 31: Preparation of specimens in a gyratory press*, PKN, Warsaw, Poland, 2019.

[15] *Instruction for laboratory testing of asphalt interlayer grafting according to Leutner's method and technical requirements for grafting*, GDDKiA, Department of Road Engineering, Gdansk University of Technology, Version of 31.08.2014

[16] *EN 12390-3 Concrete testing - Part 3: Compressive strength of test specimens*, CEN, 2019.

[17] *PN-B-06714-23:1984 Mineral aggregates - Testing - Determination of volumetric changes by Amsler's method*, PKN: Warsaw, Poland, 1984.

[18] *EN 13286-51 Unbound and hydraulically bound mixtures - Part 51: Method for industrial testing of hydraulic-binder bound samples by vibratory hammer compaction*, CEN, 2005.

[19] Raczkiewicz W., “Shrinkage of concrete - features relevant to design of concrete structures”, *Przeglad Budowlany*, vol. 2, (2012), 43-46 (in polish).

[20] Neville A.M., *Properties of concrete*, Stowarzyszenie Producentów Cementu, Cracow, 2012 (in polish).