Marta NALEWAJKO

CONCRETES MEETING THE REQUIREMENTS OF SUSTAINABLE CONSTRUCTION

Marta **Nalewajko** (ORCID: 0000-0002-2458-7147) – *Faculty of Civil and Environmental Engineering, Bialystok University of Technology, Bialystok, Poland*

Correspondence address:
Wiejska Street 45E, 15-351 Bialystok, Poland
e-mail: m.nalewajko@pb.edu.pl

ABSTRACT: The article concerns the production of lightweight geopolymer concretes based on raw materials from alkali-activated waste, which is consistent with the doctrine of sustainable construction. Fly ash, which is the main component of these geopolymer composites, constitutes energy waste and causes lower emissions of greenhouse gases and other pollutants than traditional cement. The article presents the optimisation of the geopolymer concrete recipe with different dosages of fly ash (200, 300, 400, 500, 600 and 700 kg/m^3) and two recipes, the first of which is based on the use of fly ash aggregate, the largest fraction of which was subjected to surface impregnation, and the second one is based on the use of aggregate without any impregnation. Both recipes use an alkaline solution for alkaline activation with a concentration of 6 mol/dm^3. Compressive strength tests and apparent density were carried out on the samples. The adequacy of the use of surface impregnation has been demonstrated in the case of low fly ash content (<500 kg/m^3), and the optimal recipe based on fly ash in the amount of 600 kg/m^3 was indicated.

KEYWORDS: sustainable construction, geopolymers, industrial waste, alkaline activation

Introduction

One of the fundamental issues in the construction sector recently is sustainable development, which appears not only in the literature but also in many legal regulations introduced in recent years. According to the EU guidelines (European Commission, 2021), by 2030, all new buildings constructed in European Union countries are to be buildings with zero CO2 emissions, and by 2050 the existing building resources should be transformed into zero-emission buildings. According to sustainable construction, facilities should be designed and built to be environmentally friendly. Therefore, it is particularly important to develop technologies for the production of materials that will allow the elimination of ingredients that negatively affect the environment and replace them with ingredients that cause a smaller carbon footprint. When such ingredients are also wasted, we can talk about a closed loop. However, the newly created material should have properties that are not deteriorated compared to the original materials. The use of recycled waste raw materials has recently enjoyed great interest in the construction industry, especially in relation to those that can be used in the production of cement and non-cement composites. This not only eliminates the problem of storing them in specially prepared landfills but also contributes to reducing the consumption of natural raw materials and allows the material to be reprocessed, giving it a second life.

Literature review

There are many studies on the possibility of using various wastes to produce cement and cementless composites. In 2024, González-Betancur published an article in which he described research involving the addition of waste in the form of Styrofoam to the production of concrete. He showed that the addition of recycled Styrofoam resulted in a 21.5% reduction in density, which potentially results in cost savings by reducing the size of structural elements and improving thermal and acoustic insulation. This research confirms the potential of sustainable construction using the waste described and highlights the importance of improving activation parameters to achieve optimal performance (González-Betancur et al., 2024).

Zafar, in turn, in his research described in 2024, presented the possibility of using used glasses to create alkali-activated materials. He analysed the reuse of seven different types of waste glass to create geopolymer and cement composites as sustainable building materials, focusing in particular on how the use of waste glass as a raw material in alkali-activated materials affects the durability, microstructure, hydration products and properties of the fresh mix and hardened composite compared to composites using traditional raw materials. He showed that cullet is a valuable raw material due to its low weight, excellent thermal and chemical durability, and solid insulating properties that can be used in many ways. However, the efficiency of the foaming process also depends on several inherent characteristics of the glass used, including the type of glass, its fineness and reactivity, as well as the foaming agent and sintering temperatures and time frames (Zafar et al., 2024).

In 2024, Xu also presented research involving the production of sustainable concrete by using recycled aggregates from steel waste (IOT) and construction waste (RCA) to replace natural sand. He analysed the compressive strength, peak strain, modulus of elasticity, energy dissipated in compression, and the compressive stress-strain curve. He also investigated the microstructural characteristics of the interfacial transition zone using a scanning microscope and the pore structure of concrete using nuclear magnetic resonance. According to his research, replacing quartz sand with 30% of aggregates from steel waste led to a reduction in porosity and microcracks, which resulted in a much denser microstructure. He also showed that the appropriate content of aggregates from waste steel can improve the properties of concretes based on natural aggregates and recycled construction aggregates, as well as optimise the mechanical and deformation properties of concretes based on recycled construction aggregates. However, it should be noted that they weaken the compressive strength of the concrete (Xu et al., 2024).

Other recycled materials that can be used to produce cement and non-cement concrete were described by Tuisk in an article from 2024. He presented demolition waste from a wall made of silicate-lime brick, which was used as a substitute for aggregate in the production of mortars and concrete. He showed that replacing natural aggregate (limestone rubble and sand) by up to 50% with recycled silicate brick aggregate does not significantly affect the functional properties of concrete, and he did not observe a significant decrease in compressive strength. The frost resistance of concrete made from recycled aggregate even exceeded the reference result, probably due to the lower density and higher porosity of the recycled aggregate. However, challenges such as increased water demand and loss of workability over time are noted with a higher percentage of recycled aggregate. The results suggest that recycled calcium silicate brick holds promise as a sustainable alternative to natural aggregate in concrete production (Tuisk et al., 2024).

Another example of a recycled material used in concrete is carbon fibre, the effectiveness of which was demonstrated by Patchen in a 2023 article. Carbon fibre is an attractive material for structural applications due to its lightweight, high elastic modulus, high strength, low density, and resistance to degradation. It is a good alternative to traditional steel fibre reinforcement for the production of light and durable concrete. Moreover, it offers a sustainable, cost-effective and less energy-intensive solution for infrastructure applications. The article presents the possibility of using it for high-strength concrete, lightweight structural concrete and ultra-light concrete, presenting the properties of the resulting composites. The author presented progress in the implementation of structures without steel reinforcement by ensuring the required compressive, adequate tensile, bending and shear properties and a significant reduction in the carbon footprint in the case of composites using recycled carbon fibres compared to traditional concretes with steel fibres (Patchen et al., 2023).

Taking into account recent achievements in research on cement and cement-free composites based on waste raw materials, this article presents a proposal for the production of cement-free concretes based on alkaline-activated artificial aggregates.

Research methods

The aim of the research was to optimise the recipe in such a way as to obtain samples with the highest compressive strength of alkali-activated lightweight concrete based on energy waste raw materials. The test was carried out based on silica fly ash, fly ash aggregate and an alkaline solution with a concentration of 6 mol/dm^3, and the recipe was developed in accordance with Table 1 and with the tightness condition calculated analytically according to the formula (1). For each series, 10 cubic samples with sides of 10 were prepared cm, of which 5 samples were used for compressive strength testing and the remaining 5 for apparent density testing. A total of 120 samples were performed.

Table 1. Ingredients for the preparation of lightweight concrete based on alkaline-activated waste raw materials

Ingredients	Quantity
Silica fly ash	depending on the series (200 g – 700 g)
Artificial aggregate, fraction 0-9 mm	depending on the series
Alkaline solution	alkali/ash = 0.50

Samples of lightweight concrete based on waste raw materials in the form of silica fume and ash-grain aggregate activated with an alkaline solution were prepared in accordance with the recipe presented in Table 9 – assuming that in the first stage in all series, the ash-clay aggregate of the 4-9 mm fraction will be impregnated on the surface with an alkaline solution, and in the second stage, the aggregate will be stripped of this impregnation. Table 1 below presents the ingredients for preparing lightweight concrete based on raw materials from alkaline-activated waste.

The compositions of the mixtures were designed according to the formula:

$$A + \frac{p}{\rho_p} + \frac{K}{\rho_k} = 1\,000\ dm^3 \quad (1)$$

where:
A – alkaline solution [dm^3],
p – silica fly ash [kg],

DOI: 10.34659/eis.2024.90.3.875

ρ_p – density of silica fly ash [kg/m^3],
K – artificial aggregate of individual fractions [kg],
ρ_k – density of aggregates of individual fractions [kg/m^3].

For the production of lightweight concrete based on alkaline-activated waste raw materials, silica fly ash, fly ash artificial aggregate of fractions 0–2 mm, 1–4 mm and 4–9 mm and an alkaline solution with a concentration of 6 mol/dm^3 were used. It was assumed that 10 samples would be made for each series, assuming a variable recipe.

In the first series, the mixture was made by measuring the appropriate amount of each ingredient. The aggregate of the 4–9 mm fraction was impregnated with an alkaline solution on the surface for 10 s, then sieved, removing excess solution, and weighed. Cement and rock ash aggregate of fractions 0–2 mm and 1–4 mm were poured into the mixer drum. All ingredients were mixed for 60 s, then the mixer was stopped, and the ingredients were mixed manually. The ingredients were mixed again for 60 s after stopping, the drum was filled with an impregnated aggregate of the 4-9 mm fraction and an alkaline solution of appropriate concentration, and all contents were mixed for 60 s. The mixer was stopped for the fourth time, and the ingredients were mixed manually to loosen the ingredients from the drum walls, and the device was turned on again for 60 s. The last step was repeated twice. The entire mixing process took 5 minutes.

In the second stage, the mixture was made by measuring the appropriate amount of each ingredient. Cement and ash aggregate of all fractions were poured into the mixer drum. The dry ingredients were mixed for 30 s, and after adding the alkaline solution, the wet ingredients were mixed again for 60 s. The mixer was stopped, and the ingredients were mixed manually to loosen them from the drum walls. The ingredients were mixed again for 60 seconds to obtain a ready mixture for moulding. The entire mixing process took 2.5 minutes.

In both cases, the ready mixture was placed in steel moulds with dimensions of 10×10×10 cm (compliant with the PN-EN 12390-1 standard), previously coated with grease to protect them against the adhesion of the mixture. It was decided to compact the forms by vibro-vibro-pressing, using vibration for 30 s, and then vibro-pressing for another 30 s. The samples were left for 24 h in an air-dry state and then placed in a dryer heated to 60°C for another 24 h. After that, the samples were de-moulded and placed above water for 3 days, after which tests were performed for compressive strength and apparent density.

Results of the research

Samples of lightweight geopolymer concrete based on artificial ash aggregate, not impregnated on the surface, containing 200 kg/m^3 of ash, obtained compressive strength results ranging from 0.9 MPa – 1.4 MPa, with an average of 1.14 MPa. Samples containing 300 kg/m^3 of ash had compressive strength results ranging from 4.4 MPa – 6.0 MPa, with the average being 4.83 MPa. However, samples containing 400 kg/m^3 of ash obtained compressive strength results ranging from 7.40 MPa – 9.10 MPa, with an average of 8.19 MPa. In the case of an ash content of 500 kg/m^3, the samples obtained compressive strength results ranging from 19.20 MPa – 20.30 MPa, with an average of 19.66 MPa. Samples of lightweight geopolymer concrete based on artificial ash aggregate containing 600 kg/m^3 of ash had compressive strength results ranging from 28.70 MPa – 34.20 MPa. The average strength is 30.84 MPa. Samples with 700 kg/m^3 of ash obtained compressive strength results ranging from 23.80 MPa – 27.20 MPa, with an average of 26.52 MPa.

Figure 1 below shows the results of the compressive strength of lightweight geopolymer concrete based on artificial ash aggregate, not impregnated on the surface, and fly ash activated with an alkaline solution of NaOH and water glass at a concentration of 6 mol/dm3 with various ash contents in their compositions.

In the next stage of the research, samples of lightweight geopolymer concrete based on artificial ash aggregate impregnated on the surface were tested. Samples containing 200 kg/m^3 of ash obtained compressive strength results ranging from 4.95 MPa – 6.90 MPa. The average compressive strength was 6.11 MPa. Samples with 300 kg/m^3 ash had compressive strength results ranging from 14.10 MPa – 16.10 MPa, with an average compressive strength of 15.02 MPa. However, samples containing

DOI: 10.34659/eis.2024.90.3.875

400 kg/m^3 of ash showed compressive strength in the range of 16.10 MPa – 19.40 MPa. The average compressive strength was 17.40 MPa. In the case of an ash content of 500 kg/m^3, the samples obtained compressive strength results ranging from 21.40 MPa – 24.10 MPa, and the average was 22.86 MPa. Samples of lightweight geopolymer concrete based on artificial ash aggregate containing 600 kg/m^3 of ash obtained compressive strength results ranging from 22.40 MPa – 25.20 MPa, with an average strength of 23.92 MPa. Samples containing 700 kg/m^3 of ash had compressive strength results ranging from 18.50 MPa – 23.10 MPa. The average compressive strength was 21.40 MPa.

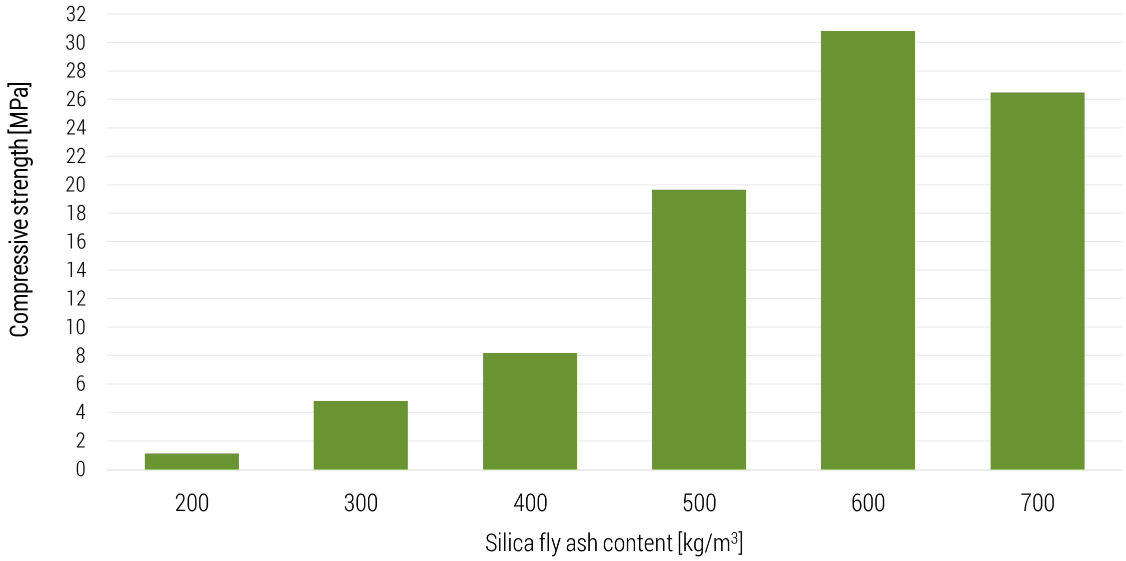

Figure 1. Compressive strength of lightweight concrete based on alkali-activated waste raw materials containing non-surface impregnated aggregate

Figure 2 illustrates the results of the compressive strength of lightweight geopolymer concrete based on artificial ash aggregate, not surface-impregnated, and fly ash activated with an alkaline NaOH solution at a concentration of 6 mol/dm3 with various ash contents in their compositions.

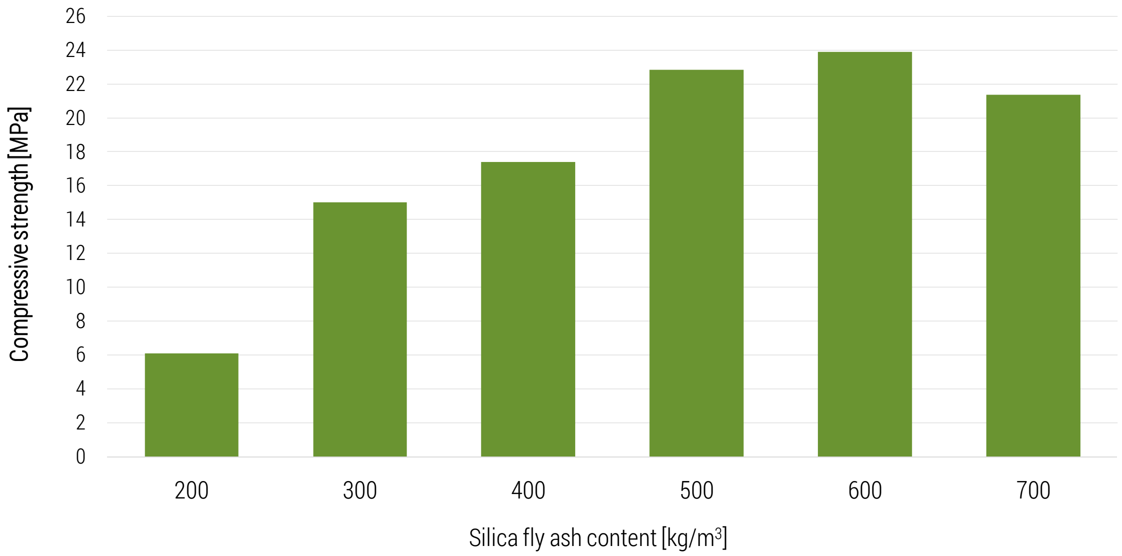

Figure 2. Compressive strength of lightweight concrete based on alkali-activated waste raw materials containing surface-impregnated aggregate

DOI: 10.34659/eis.2024.90.3.875

Figure 3 below shows a comparison of the compressive strength of lightweight geopolymer concrete with various silica fly ash compositions based on surface-impregnated and non-surface-impregnated, alkali-activated fly ash aggregate.

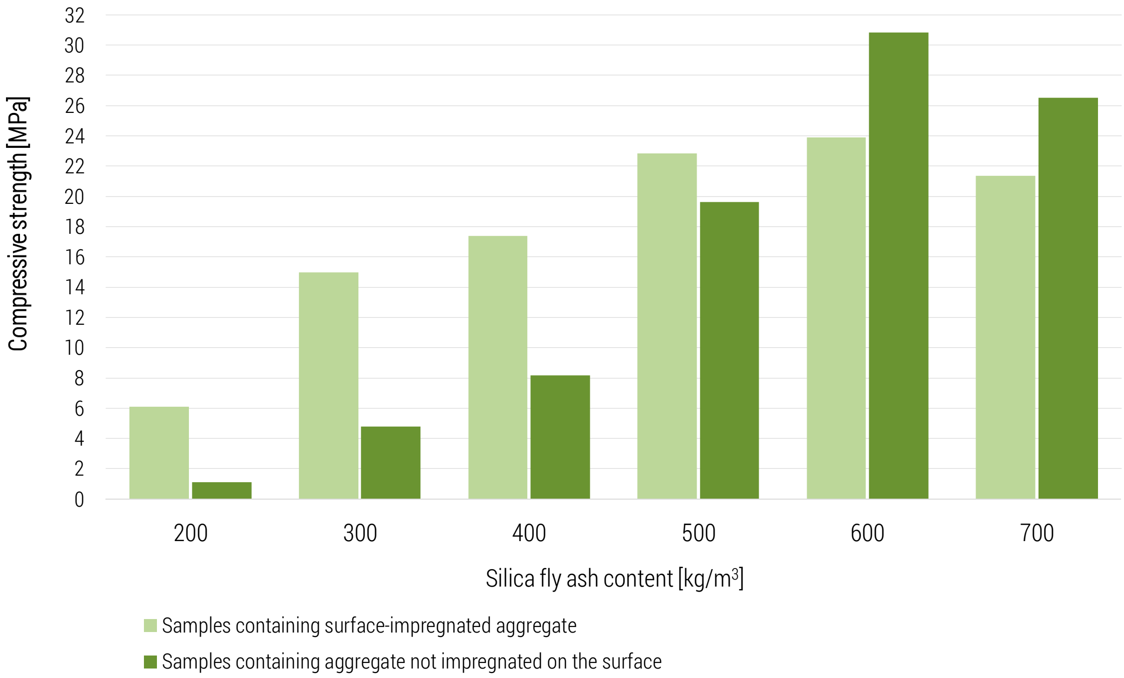

Figure 3. Compressive strength of lightweight concrete with different fly ash compositions, based on surface-impregnated and non-impregnated fly ash artificial aggregate, activated with alkali

Samples of lightweight geopolymer concrete with various fly ash contents based on waste raw materials activated with alkaline NaOH solution and water glass at a concentration of 6 mol/dm^3, containing coarse aggregate not impregnated on the surface, were also tested, taking into account the apparent density.

Samples containing 200 kg/m^3 of fly ash obtained apparent density results of approximately 1285.50 g/cm^3 – 1354.00 g/cm^3, with an average of 1306.80 g/cm^3. Samples containing 300 kg/m^3, apparent density ranging from 1459.00 g/cm^3 to 1481.00 g/cm^3. The average apparent density was 1470.30 g/cm^3. However, samples with 400 kg/m^3 of fly ash obtained apparent density results ranging from 1454.50 g/cm^3 – 1564.00 g/cm^3, where the average apparent density was 1519.90 g/cm^3. For samples containing 500 kg/m^3 of fly ash, the apparent density is approximately 1639.00 g/cm^3 – 1674.00 g/cm^3. The average apparent density was 1653.90 g/cm^3. Samples containing 600 kg/m^3 obtained apparent density results in the range of 1642.50 g/cm^3 – 1656.50 g/cm^3, the average was 1651.90 g/cm^3. However, samples containing 700 kg/dm^3 of fly ash obtained apparent density results ranging from 1639.50 g/cm^3 – 1660.50 g/cm^3. The average apparent density was 1651.10 g/cm^3.

Figure 4 shows the results of the apparent density of lightweight concrete based on artificial ash aggregate, not impregnated on the surface, and fly ash activated with an alkaline solution at a concentration of 6 mol/dm^3 with different ash contents in their compositions.

In a further stage of the research, the apparent density of lightweight geopolymer concrete samples with various ash contents was checked based on waste raw materials activated with an alkaline solution of NaOH and water glass at a concentration of 6 mol/dm^3 containing coarse aggregate impregnated on the surface.

Samples containing 200 kg/m^3 of fly ash had apparent density results of approximately 1491.00 g/cm^3 – 1538.50 g/cm^3. The average apparent density was 1514.70 g/cm^3. Samples containing 300 kg/m^3 obtained apparent density results in the range of 1640.00 g/cm^3 – 1753.00 g/cm^3. The average apparent density was 1698.40 g/cm^3. However, samples containing 400 kg/dm^3 of fly ash obtained apparent density results ranging from 1807.50 g/cm^3 – 1859.50 g/cm^3. The average apparent density was 1831.50 g/cm^3. Samples containing 500 kg/m^3 of fly ash obtained apparent density results of

DOI: 10.34659/eis.2024.90.3.875

approximately 1761.00 g/cm^3 – 1792.00 g/cm^3. The average apparent density was 1780.18 g/cm^3. Samples containing 600 kg/m^3 obtained apparent density results in the range of 1702.50 g/cm^3 – 1729.00 g/cm^3, with an average of 1713.50 g/cm^3. However, samples containing 700 kg/dm^3 of fly ash obtained apparent density results ranging from 1653.50 g/cm^3 – 1660.00 g/cm^3. The average apparent density was 1651.10 g/cm^3.

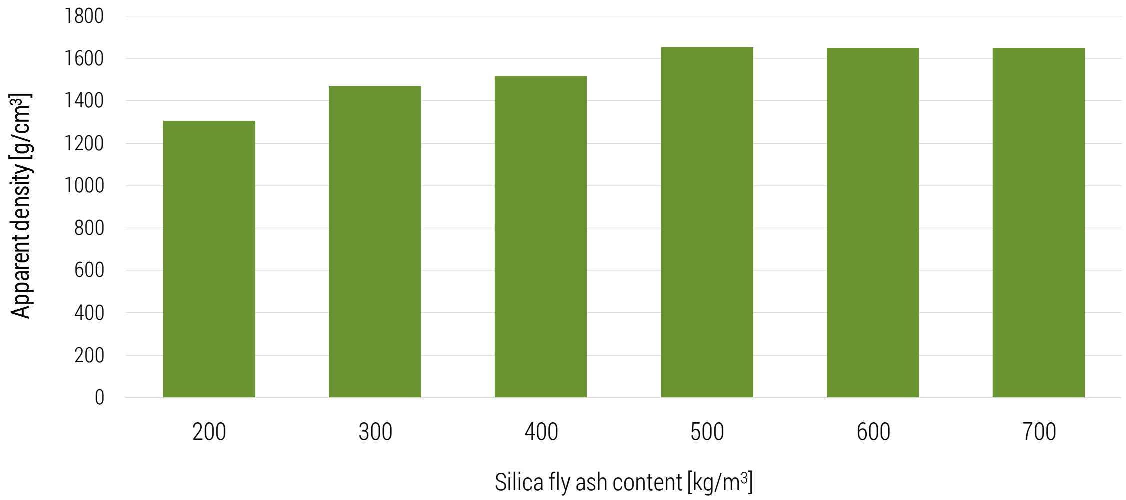

Figure 4. Apparent density of lightweight concrete with various ash contents in its compositions, based on ash-poured artificial aggregate, not surface-impregnated, alkaline-activated

Figure 5 shows the results of the apparent density of lightweight concrete based on artificial ash aggregate, not surface-impregnated, and fly ash activated with an alkaline solution of NaOH at a concentration of 6 mol/dm^3.

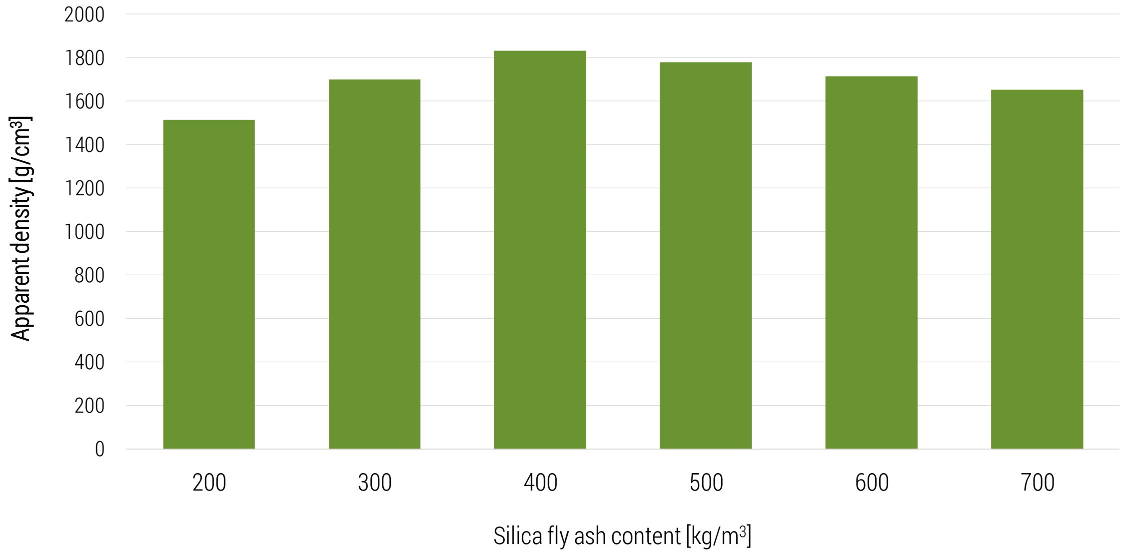

Figure 5. Apparent density of lightweight concrete with various ash contents in its compositions, based on alkali-activated waste raw materials containing surface-impregnated aggregate

Figure 6 shows a comparison of the apparent density of lightweight concrete with different ash contents in their compositions based on surface-impregnated and non-surface-impregnated fly ash aggregates and alkali-activated fly ash.

DOI: 10.34659/eis.2024.90.3.875

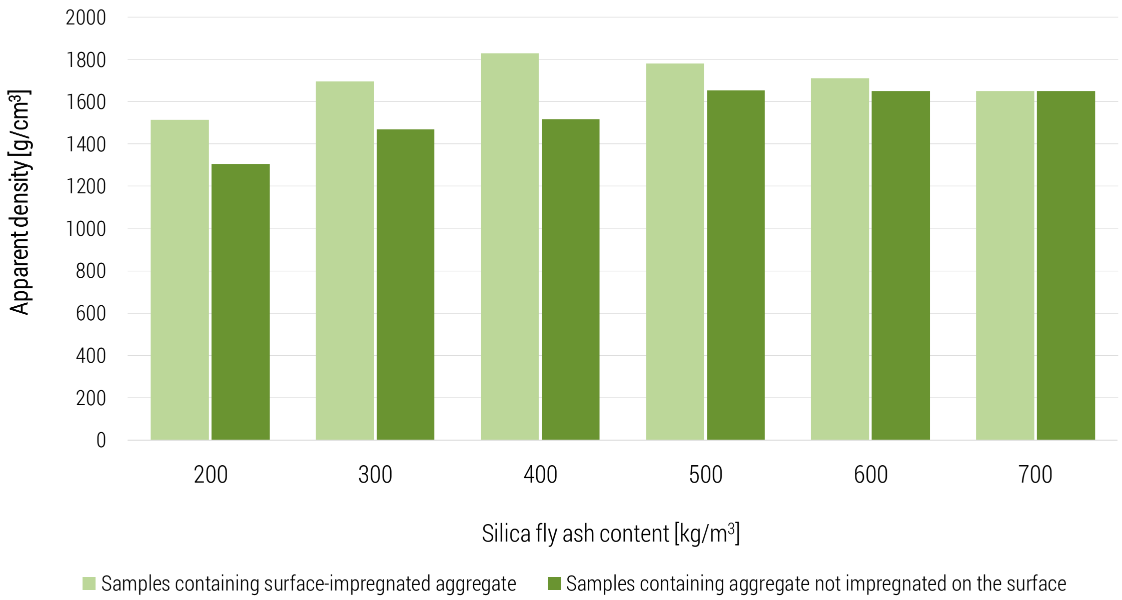

Figure 6. Apparent density of lightweight concrete with various ash contents in their compositions, based on ash-impregnated and non-surface-impregnated artificial aggregates, alkali-activated

Conclusions and future research

The analysis of the conducted research shows that:

- it is possible to monolithically combine alkaline-activated waste raw materials and obtain composites with good physical and mechanical properties,
- the use of industrial waste raw materials allows the composites to be classified as those that fit into the doctrine of sustainable construction,
- the highest compressive strength is obtained with a silica fly ash content of up to 600 kg/m^3,
- in all recipes, the apparent density result is within the standards, allowing the samples to be classified as lightweight concretes,
- slight differences were found in the apparent density in the series containing both impregnated and non-impregnated aggregates,
- the use of surface impregnation of coarse aggregate is adequate in the case of a smaller amount of ash in the recipe (<500 kg/m^3) and leads to an even two-fold difference in compressive strength results.

In further research, recipes will be adopted based on fly ash content of 200, 400 and 600 kg/m3 using various concentrations of activators from 2 to 10 moles/dm^3.

References

European Commission. (2021). Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast), Pub. L. No. 52021PC0802. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802

González-Betancur, D., Hoyos-Montilla, A. A., & Tobón, J. I. (2024). Sustainable Hybrid Lightweight Aggregate Concrete Using Recycled Expanded Polystyrene. Materials, 17(10), 2368. https://doi.org/10.3390/ma17102368

Patchen, A., Young, S., Goodbred, L., Puplampu, S., Chawla, V., & Penumadu, D. (2023). Lower Carbon Footprint Concrete Using Recycled Carbon Fiber for Targeted Strength and Insulation. Materials, 16(15), 5451. https://doi.org/10.3390/ma16155451

PN-EN 12390-1. Testing hardened concrete – Part 1: Shape, dimensions and other requirements for specimens and moulds.

Tuisk, T., Ilomets, S., Hain, T., Kalbus, J., & Kalamees, T. (2024). Rheology, Strength, and Durability of Concrete and Mortar Made of Recycled Calcium Silicate Masonry. Materials, 17(12), 2790. https://doi.org/10.3390/ma17122790

Xu, W., Li, Z., Li, T., & Wang, S. (2024). The Mechanical Properties and Microstructure of Tailing Recycled Aggregate Concrete. Materials, 17(5), 1058. https://doi.org/10.3390/ma17051058

Zafar, M. J., Elsayed, H., & Bernardo, E. (2024). Waste Glass Upcycling Supported by Alkali Activation: An Overview. Materials, 17(9), 2169. https://doi.org/10.3390/ma17092169

Marta NALEWAJKO

BETONY SPEŁNIAJĄCE WYMAGANIA BUDOWNICTWA ZRÓWNOWAŻONEGO

STRESZCZENIE: Artykuł dotyczy wykonania lekkich betonów geopolimerowych na bazie surowców odpadowych aktywowanych alkalicznie wpisujących się w doktrynę budownictwa zrównoważonego. Popiół lotny stanowiący główny składnik danych kompozytów geopolimerowych stanowi odpad energetyczny i powoduje niższą emisję gazów cieplarnianych i innych zanieczyszczeń niż tradycyjny cement. W artykule przedstawiono optymalizację receptury betonów geopolimerowych przy zróżnicowanym dozowaniu popiołu lotnego (200, 300, 400, 500, 600 i 700 kg/m^3) oraz dwóch receptur, z których pierwsza bazuje na wykorzystaniu kruszywa popiołoporytowego, którego największa frakcja została poddana impreganacji powierzchniowej, a druga bazuje na wykorzystaniu kryszywa bez danej impregancji. W obu recepturach do aktywacji alkalicznej wykorzystano roztwór alkaliczny o stężeniu 6 mol/dm^3. Na próbkach przeprowadzono badanie wytrzymałości na ściskanie i gęstości pozornej. Wykazano adekwatność stosowania impregnacji powierzchniowej w przypadku małej zawartości popiołu lotnego (<500 kg/m^3) oraz wskazano optymalną recepturę bazującą na popiele lotnym w ilości 600 kg/m^3.

SŁOWA KLUCZOWE: zrównoważone budownictwo, geopolimery, odpady przemysłowe, aktywacja alkaliczna