Marta NALEWAJKO

USE OF WASTE MATERIALS IN ALKALINE-ACTIVATED LIGHTWEIGHT CONCRETE

Marta **Nalewajko,** MsC (ORCID: 0000-0002-2458-7147) – *Białystok University of Technology*

Correspondence address:
Daliowa Street 20, 16-010, Nowodworce, Poland
e-mail: m.nalewajko@doktoranci.pb.edu.pl

ABSTRACT: The article presents the concept of using energy waste as an alternative material to natural aggregate and cement, which is one of the elements of sustainable construction. Because the amount of ash produced annually by power plants is very high, its use in the construction sector would allow for its significant elimination from the landfills of polluting components. The use of ash as a substitute for cement, as well as the replacement of natural aggregate by ash sintering process for the production of light concretes would be a big step towards sustainable construction, whose integral point is the implementation of technologies allowing for the integration of construction with the environment. Current knowledge allows for the development of technologies for the production of lightweight concretes based on energy waste materials using alkalis with properties similar to or better than those of traditional lightweight concretes. This is extremely important from environmental protection, and at the same time is an alternative technology for the production of lightweight concretes when natural resources are exhausted.

KEYWORDS: waste raw materials, ash aggregate, concrete, lightweight concrete, sustainable construction

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Introduction

The main idea of sustainable construction is to design, build and use buildings and structures that interact with the surrounding environment and do not pollute it with various types of waste, thus making the use of the facilities friendly for both users and the environment. The main assumption of this idea is primarily the durability and quality of design, construction and material solutions, but also the availability and comfort of the designed buildings and structures, taking into account the aspects protecting the environment against pollution. In the modern world, more and more importance is being attached to the preservation of green areas and resting places that blend in with built-up areas.

Taking into account the priorities of sustainable construction principles, the aim is to reduce energy consumption and ensure that future generations can benefit from depleting natural resources. This is particularly important in the housing sector, where its visible development has increased demand for natural resources in the form of aggregates or water, used for the production of concrete, which is the main material used in modern construction. The decreasing number of plants extracting natural aggregates, destroying the environment and the amount of research carried out on the use of alternative raw materials for the production of concrete, testify to the growing awareness of the society and less consent to the use of natural resources. Therefore, it is particularly important to replace natural aggregate with secondary aggregate in the production of construction products, with increasing demand for it.

Production of geopolymers can be a viable alternative to the management of certain waste from the energy, mining and metallurgical sectors, especially fly ash. This makes it possible to use significant amounts of energy waste and to produce new products, and thus partially minimize the negative impact of these factors on the environment. Many years of research have allowed the use of fly ash for the production of concrete and showed its positive impact on the physical and mechanical properties of the final product. Fly ash showing the pozzolanic properties improves the properties of concrete, accelerating the hydration of cement at an early stage, increasing the amount of water bound in the C-S-H phase, resulting in an increase in the final strength of concrete or increasing its durability.

This article focuses in particular on the properties of lightweight concrete based on alkaline activated waste materials. This is important, not only because of the replacement of cement with ash, thus causing the disposal of an excessive amount of building or industrial waste, but also the use in the mix of ash-bearing aggregate resulting from the sintering of the energy resource in place of natural aggregate. Therefore, in addition to the problem of a decreasing amount of aggregates, there is also a problem related to greenhouse gas emissions from cement production processes. The use of fly-ash and aggregate formed from fly-ash is aimed at the complete elimination of Portland cement from the concrete composition, the production of which results in the emission of greenhouse gases in the range of 7-8% on a global scale, including the emission of CO_2 constituting almost a half of the emitted gases and minimizing the consumption of natural aggregates, which are nowadays a valuable raw material. The production of geopolymers may therefore lead to a significant reduction of the environmental burden.

Related research

The research carried out on geopolymeric composites produced by alkaline activation of waste materials has led to the development and development of technologies for their obtaining. One of the first people in the world to receive a binder based on fly ash by its activation with sodium hydroxide were Anna Derdacka-Grzymek and Andrzej Stok (Rajczyk, Giergiczny, Szota, 2015). They carried out a number of studies which allowed to establish that the binding and hardening of geopolymeric binders based on fly ash is caused by dissolving the active components of ashes in sodium hydroxide solution (Derdacka-Grzymek, Stok, 1980).

In 1999, Palomo A., Grutzeck M.W. and Blanco M.T. described the mechanism of fly ash activation with strong alkaline solutions. The product of the reaction was amorphous aluminosilicate gel with a structure similar to that of zeolites. It was shown that temperature and curing time significantly increase the mechanical strength of the final product.

Van Jaarsveld J.G.S. Van Deventer J.S.J. published a study in the same year which showed the effects of Na+ and K+ on the physical and chemical properties of fly ash geopolymers, both before and after bonding. It was found that alkaline metal cation controls and influences almost all stages of geopolymerization, from ordering of ions and soluble compounds during the dissolution process to the role of structure guiding during gel curing and final crystal formation.

In 2002, Swanepoel J.C. and Strydom C.A. investigated fly ash, a waste product from the energy and petrochemical industries, as a basic component of a new geopolymeric material. Many analyses showed that the optimum firing temperature is 60°C for 48 hours.

Hardjito D., Wallah S.E., Sumajouw D.M.J. and Rangan B.V. published a scientific paper in 2004, presenting the development of fly-ash based geopolymer concrete. The results of the research showed the influence of various parameters on the properties of geopolymer concrete. The application of geopolymer concrete was also identified and the scope of future research needs was determined.

Hardjito D., Wallah S.E. and others at the same time presented the influence of the mixture composition on the compressive strength of fly ash-based geopolymer concrete. The results showed that the molar ratio of water to sodium oxide and the ratio of water to geopolymer by mass affect the compressive strength of fly ash-based geopolymer concrete. The compressive strength decreases as these coefficients increase. They have also published further studies in which they attempted to investigate the properties of fresh geopolymer concrete. The compressive strength of geopolymer concrete increased with an increase in NaOH concentration, as well as with an increase in alkaline solution concentration. The compressive strength was even higher than that of conventional concrete at 14M concentration. Subsequent tests were carried out for changes in compressive strength of geopolymer concrete taking into account age, curing of concrete samples at a higher temperature and longer curing period.

In 2005, Song X.J., Marosszeky M. and others presented experimental data on the durability of volatile ash-based geopolymer concretes treated with 10% sulphuric acid solutions for up to 8 weeks. The results confirmed that geopolymer concretes are highly resistant to sulphuric acid in terms of very low weight loss, below 3%. Moreover, the geopolymer cubes were structurally intact and still had a significant load-bearing capacity, although the whole section was neutralised with sulphuric acid.

In 2009, Wallah S E. prepared four series of samples of different compression strength to test the shrinkage of drying geopolymer concrete. He then compared the test results with the calculated dry shrinkage results, according to the Gilbert method, which is usually applied to ordinary Portland cement. The tests showed that geopolymer concrete based on heat-cured fly ash is subject to very small shrinkage during drying.

Studies by Lloyd L.A. and Rangan B. V. were described in an article published in 2010 and presented the stages of the experiment carried out on geopolymer concrete based on fly ash. The test data were used to identify the influence of significant factors that affect the properties of the geopolymer mixture as well as the hardened geopolymer.

In the simultaneous analysis of Diaz E. I., Allouche E. N. and Eklund S. examined the suitability of fly ash piles for geopolymer production. They presented the results of chemical analyses, X-ray diffraction (XRD) and particle size distribution (PSD) of five sources of fly ash obtained from coal-fired power plants in the USA. Geopolymer paste and concrete samples were prepared from each stack. The samples were subjected to a number of chemical and mechanical tests, stating that factors related to the composition of fly ash, such as particle size distribution, degree of glazing and location of maximum glass diffraction play an important role in the fresh and cured properties of the resulting geopolymer.

Olivia M. and Nikraz H.R. presented studies on strength development, water absorption and water permeability in low calcium ash geopolitical concrete. No significant change in water permeability coefficient was found for a geopolymer with different parameters. The data from the studies showed that with proper parameterization and mixture design, good quality geopolymer concrete with low calcium ash content can be obtained.

Extensive laboratory tests on compression strength were also conducted in India by Prakash R.V. and Dave U.V., and their results are presented in the "Parametric Studies on Compressive Strength of Geopolymer Concrete" published in 2013. Twenty series were performed and various parameters were examined, where the results showed that the compressive strength increases with increasing curing time, curing temperature, resting period, sodium hydroxide solution concentration and decreases with increasing ratio of water to geopolymer solids to the mass and admixture dose respectively. The addition of a naphthalene based superplasticizer improved workability of fresh geopolymer concrete. Moreover, it was observed that water content in the mixture of geopolymer concrete plays a significant role in achieving the desired compressive strength.

Polish scientists from Mazury P., Mikuła J. in 2013 presented research on geopolymer as a new engineering material from which protective layers can be formed. They showed that it has a high ability to absorb moisture, but its composition is strongly alkaline and thus its soaking does not adversely affect the protected structure.

Ghosh R., Kumar A. and others published a scientific article presenting the scope of research on Fly Ash based geopolymer concrete as a future concrete, summarizing and critically analysing the most important results of the conducted analyses.

In 2014, Chen R., Ahmari S. and Zhang L. investigated the strengthening of the fly ash geopolymer with pre-treated alkaline sweet sorghum fibre. The results showed that the unit weight of the composite decreased with increasing fibre content. The inclusion of sweet sorghum fibre slightly reduces the compressive, tensile and bending strength, as well as causes an increase in peak impact strength with fibre content up to 2%, which then begins to decrease.

Abdollahnejad Z., Pacheco-Torgal F. and others studied the common impact of several parameters of the mixture on the properties of foam geopolymers. The blends with low thermal conductivity of about 0.1 W/(m-K) and compressive strength of about 6 MPa were obtained.

In 2016, Sarmin S.N. and Welling J. presented the basic mechanical and physical properties of geopolymer composites based on fly ash/methacaolin reinforced with wood particles 3-5 mm in size. They made samples with dimensions of 50×50×50 mm^3 which were subjected to compression in order to obtain basic mechanical properties and determine optimal proportions of fly ash and methacaolin. It was observed that the inclusion of different types of wood raw materials affected the properties of geopolymers. It was shown that the size and shape of wood aggregates affect the properties of geopolymer composites.

The article published in 2016 by Xiao Yu Zhuang Liang C., Sridhar K. and others summarizes and analyzes scientific progress in the preparation, the study of the properties and application of fly ash-based geopolymers. The production was mainly based on alkaline activated geopolymerization, which can take place under mild conditions and is considered to be a cleaner process due to significantly lower CO_2 emissions than cement production. The main problems concern the mechanical properties of the fly ash-based geopolymer, including compressive strength, bending and tensile strength and durability and resistance to chlorine, sulphate, acid, heat, freeze-thaw and blooms.

Research on geopolymers based on fly ash was started in the 1980s and is still carried out around the world. Geopolymer samples were tested using different waste materials, activators of different concentrations, taking into account temperature and sintering time. They allowed concluding that the geopolymer composite showed much better physical and mechanical properties than ordinary concrete based on Portland cement. After analysing the national and world literature, it was decided to carry out studies on lightweight, alkaline-activated fly-ash concretes with the addition of ash aggregate, which has not yet been used in any analyses. All the studies so far have been carried out on the basis of natural aggregate with the addition of raw materials in the form of fibres, chips and wood flour and foam.

Justification of the test technology used

The requirements for modern construction products are increasingly restrictive. In addition to high strength properties, low density or low absorption capacity, they must also have adequate thermal insulation, high acoustic properties and be environmentally friendly. Integration with ecology is not only focused on the lack of negative impact on the environment, but also on the use of waste, which is not deposited on landfills and thus does not cause slow degradation of the environment. In order to meet these requirements, numerous studies are carried out to modify the composition of light concrete by replacing its basic components with alternative raw materials, assuming that the properties of the final product will not be impaired.

A number of tests carried out on lightweight concretes with modified composition allowed to draw conclusions that they meet the requirements for modern concretes. Various waste aggregates were used in their production, such as waste from the production of coconut oil (Alengaram, 2013), aggregates in the form of pumice stone, expanded perlite or waste rubber aggregates (Oktay, 2015), and in addition to artificial aggregates, additives such as sawdust, wood shavings, straw or reed were used.

The development of construction, and thus concrete consumption, has made it necessary to improve their recipe in order to determine the possibility of using substitute raw materials, so their properties are increasingly being studied, focusing not only on the properties of the aggregate itself but also the product made with it. Among the recycling aggregates, ash-ash is becoming more and more common in recent times. It is an artificial raw material, produced according to a new technology consisting in the sintering of ashes from the process of burning hard coal, leading to a lightweight, porous ceramic aggregate with high thermal insulation and high resistance to atmospheric, chemical, fungi, insects or rodents, which is an odourless, highly resistant and relatively low absorbency material. Due to its properties, it is used in construction or road construction, and for a long time, it has been used in concrete production, allowing to obtain products with reduced weight and much better strength parameters.

Studies on the properties of lightweight concrete based on alkaline-activated waste materials were conducted in stages. In the first stage, lightweight cement composites based on ash-bearing aggregate were designed as a comparative sample to alkaline-activated lightweight concretes with an average compressive strength of 10.68 MPa. In the second stage, alkaline-activated lightweight concretes were made, assuming ash to activator ratio of 2, using sodium hydroxide activators at concentrations of 2, 6, 8 and 10 mol/dm^3 and aggregates at 4 in relation to ash.

Procedure for producing lightweight concretes based on alkaline-activated waste materials and analysis of results

For the production of lightweight concretes based on alkaline-activated waste materials, ash, artificial ash aggregate of 0-2 mm, 1-4 mm and 4-9 mm fractions and NaOH solution of 2, 6, 8 and 10 mol/dm^3 concentrations were used. It was accepted to make 5 samples for each concentration of the NaOH solution.

The appropriate amount of each of the ingredients was measured. The aggregate of 4-9 mm fractions was surface impregnated with NaOH solution of appropriate concentration for 10 s, then sieved and weighed. Cement and ash-associated aggregate of 0-2 mm and 1-4 mm fractions and impregnated aggregate of 4-9 mm fractions were poured into the mixer drum. All the components were mixed for 60 s, then the mixer was stopped and the components were mixed manually. The components were mixed again for 60 s. The mixer was stopped, NaOH solution of appropriate concentration was added to the drum and everything was mixed for 60 s. For the fourth time the mixer was stopped, the components were mixed by hand in order to separate the components from the drum walls and the mixer was switched on again for 60 seconds. The last operation was repeated twice.

The finished mixture was placed in 10x10x10 cm steel moulds conforming to PN-EN 12390-1 standard, previously covered with a release agent in order to protect them from sticking the mixture. It was decided to thicken the moulds by vibro-pressing, by vibrating for 30 s. and then vibro-pressing for another 30 s. The samples were left in an air-dry condition for 24 hours and then placed in a dryer heated to 60°C for another 24 hours. After that time the samples were disassembled and placed over water for 3 days. After this period they were subjected to compression strength test with the following results:

- the samples of lightweight concrete based on artificial ash aggregate activated by alkaline NaOH solution with a concentration of 2 mol/dm^3 obtained results of compressive strength from 2.80 MPa to 5.73 MPa. The average compressive strength was 4.20 MPa,
- lightweight concrete samples based on artificial ash aggregate activated by alkaline NaOH solution with a concentration of 6 mol/dm^3 obtained results of compressive strength from 16.25 MPa to 18.00 MPa. The average compressive strength was 16.89 MPa,
- lightweight concrete samples based on artificial ash aggregate activated by alkaline NaOH solution with a concentration of 8 mol/dm^3 obtained results of compressive strength of 14.20 MPa – 14.85 MPa. The average compressive strength was 14.57 MPa,
- lightweight concrete samples based on artificial ash aggregate activated by alkaline NaOH solution with a concentration of 10 mol/dm^3 obtained results of compressive strength from 20.90 MPa to 24.20 MPa. The average compressive strength was 21.82 MPa.

Table 1 below the results of the compressive strength of individual samples are presented. In figure 1 presents a compilation of the shear strength of light alkali-activated composites with surface impregnated aggregate.

Table 1. Compressive strength of light concretes activated with alkali with NaOH solution with a concentration of 2, 6, 8 and 10 mol/dm³

	GEOPOLYMER 2M	GEOPOLYMER 6M	GEOPOLYMER 8M	GEOPOLYMER 10M
Compressive strength [MPa]	4.15	17.00	14.20	22.7
	4.10	18.00	14.70	20.1
	2.80	16.25	14.60	20.9
	3.40	16.95	14.85	24.2
	5.73	16.25	14.50	21.2
Medium compressive strength [MPa]	4.20	16.89	14.57	21.82

Source: author's work.

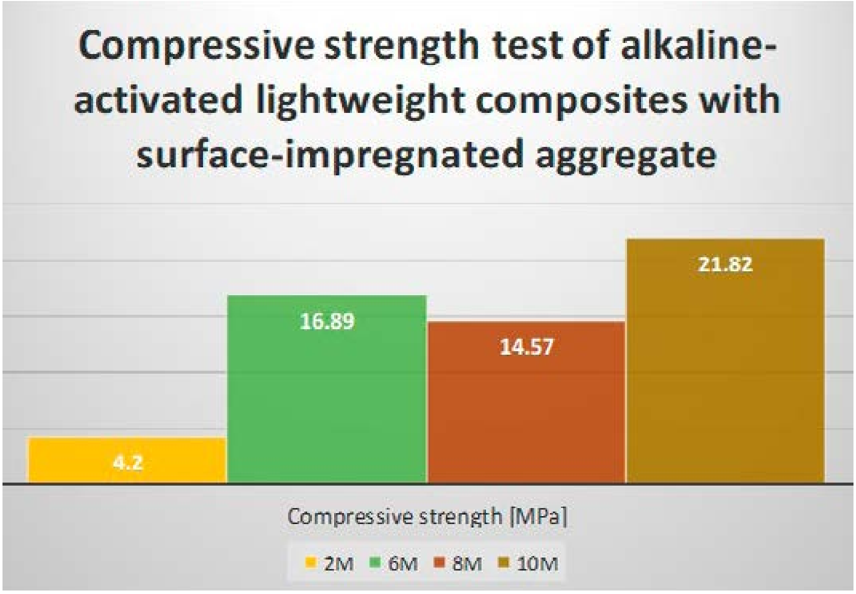

Figure 1. Compressive strength test of alkaline-activated lightweight composites with surface-impregnated aggregate

Source: author's work.

In figure 1 we can see that with the increase of NaOH concentration added to the concrete mix of lightweight concrete, the compressive strength of the finished sample increases.

It should be noted, however, that the obtained results of compressive strength are high compared to lightweight concretes based on Portland cement and ash-pore aggregate. The research of L. Domagała showed that the use of ash-pore aggregates in concrete mixes significantly reduces strength by up to 42%, up to 86% compared to traditional concrete based on natural aggregate. In the above tests, the results of strength were obtained, which do not differ from the results of traditional lightweight concretes based on ash-pore aggregate, and even show higher results due to their initial impregnation with alkali, which resulted in minimizing the water demand of the aggregate added to the concrete mix.

Conclusions

This study focused in particular on the properties of lightweight concretes based on alkaline activated waste materials. This is important not only because of getting rid of the excessive amount of residual construction or industrial waste but also due to the drastically decreasing amount of natural aggregate deposits. In addition to the problem of less and less aggregate, there is a problem with greenhouse gas emissions from cement manufacturing processes. The use of fly ash is aimed at the complete elimination of Portland cement from the concrete composition, the production of which causes greenhouse gas emissions in the range of 7-8% on a global scale, including CO_2 emissions that account for almost half of the emissions. It is estimated that the synthesis of geopolymers is twice as energy-consuming as the production of Portland cement and produces 4-8 times less carbon dioxide. The production of geopolymers can therefore lead to a significant reduction in the environmental burden.

The analysis of the research results to date shows that samples of light alkali-activated composites achieve compressive strength at a level that allows them to be used in construction instead of traditional lightweight concretes based on Portland cement. It is particularly important to emphasize that in the production of concrete samples, the ash-pore aggregate was used, which is ecological, but at the same time very difficult in the production of concrete. Their high water demand is a problem at the time of production of the concrete mix and significantly reduces the strength of the finished sample. The impregnation of the aggregate applied before adding it to the mixture allowed to eliminate the problem and obtain a sample with the appropriate compressive strength. It should also be noted that samples of light alkali-activated composites at higher concentrations have much higher strength properties. These studies show that light alkali-activated concretes based on waste materials are the future of the construction industry.

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