Romanian Journal of Civil Engineering, Volume 16 (2025), No. 1

Geopolymer concrete as an effective technical variant for reducing CO_2 emissions in the atmosphere during preparing construction materials

Beton geopolimeric ca variantă tehnică eficace pentru reducerea emisiilor de CO_2 în atmosferă în timpul pregătirii materialelor de construcție

Lucian Paunescu[1], Bogdan Valentin Paunescu[2], Enikö Volceanov[3,4], Adrian Ioana[5]

[1]Daily Sourcing & Research SRL
95-97 Calea Grivitei street, sector 1, Bucharest 010705, Romania
E-mail: lucianpaunescu16@gmail.com

[2]Consitrans SA
56 Polona street, sector 1, Bucharest 010504, Romania
E-mail: pnscbogdan@yahoo.com

[3]Metallurgical Research Institute SA
39 Mehadia street, sector 6, Bucharest 060543, Romania
E-mail: evolceanov@yahoo.com

[4]University "Politehnica" of Bucharest, Faculty of Science and Materials Engineering
313 Independence Splai, sector 6, Bucharest 060042, Romania
E-mail: evolceanov@yahoo.com

[5]University "Politehnica" of Bucharest, Faculty of Science and Materials Engineering
313 Independence Splai, sector 6, Bucharest 060042, Romania
E-mail: adyioana@gmail.com

DOI: 10.37789/rjce.2025.16.1.4

Abstract. *The improved version of geopolymer concrete manufacturing based on fly ash and granulated blast furnace slag was made by correlating the high mechanical strength of the hardened material with the medium level-workability of the fresh material. The fly ash/slag ratio in the composition of the substitute binder for Portland cement was reduced to the limit where the workability was affected, but this reduction was compensated by fluidizing additive (calcium lignosulfonate) addition. Due to the correlation of mechanical properties and those of fluidity, high compression and flexural strengths were obtained (57.4 and 10.1 MPa) after curing and 28 days-storage.*

Key words: *geopolymer concrete, alkaline activator, curing process, calcium lignosulfonate, mechanical strength, workability.*

The article was received on 27.11.2023, accepted on 05.02.2025 and published on 14.03.2025

Lucian Paunescu, Bogdan Valentin Paunescu, Eniko Volceanov, Adrian Ioana

Rezumat. *A fost realizată o versiune îmbunătățită a betonului geopolimeric fabricat pe bază de cenușă zburătoare și zgură de furnal granulată prin corelația rezistenței mecanice înalte a materialului întărit cu lucrabilitatea de nivel mediu a materialului proaspăt. Raportul cenușă zburătoare/zgură în compoziția liantului înlocuitor al cimentului Portland a fost redus la limita la care lucrabilitatea a fost afectată, dar această reducere a fost compensată de adaosul aditivului fluidizant (lignosulfonat de calciu). Datorită corelației proprietăților mecanice si acelea ale fluidității, au fost obținute rezistențe înalte la compresie și încovoiere (57,4 și 10,1 MPa) după întărire și stocare pentru 28 zile.*

Cuvinte cheie: beton geopolimeric, activator alcalin, proces de întărire, lignosulfonat de calciu, rezistență mecanică, lucrabilitate.

1. Introduction

In the current context of dangerous rate of destructing the protective ozone layer of our planet due to excessive emissions of greenhouse gases (mainly CO_2), humanity's concern for stopping or limiting this possible ecological disaster has already reached a high level since the beginning of the new millennium.

One of the industrial activity fields deeply involved in CO_2 emissions and responsible for up to 7 % of the entire CO_2 amount released worldwide is the construction material industry and primarily the manufacture of ordinary Portland cement as the essential raw material of the concrete manufacturing process [1, 2]. Also, the cement making is a high energy-intensive process, the manufacture of one ton of Portland cement requiring about 4 GJ [3] in form of fossil fuels, which generate carbon dioxide by burning.

The modern use of Portland cement as the dominant binder in the production of construction concrete is already over 180 years old [4]. During all this time, due to humanity's lack of concern for the high consumption of hydrocarbons and the dangerous emissions of pollutants in the atmosphere, the industry, in general and the cement industry, in particular, have experienced a long period of development, suddenly interrupted starting from the last decades of the last century.

Reducing the carbon footprint of cement has been tried by several researchers' teams using different cementitious materials such as fly ash, metallurgical slag, rice husk ash, red mud, metakaolin, having the role of partially replacers for the cement intended for manufacturing the concrete [3, 5-8].

According to Juenger et al. [4], recently, there is an unprecedented increase in the interest of researchers from all over the world for developing, testing, and applying new alternatives to ordinary Portland cement. Thus, calcium aluminate cement, calcium sulfo aluminate cement, super sulphated cements, and alkali-activated binders were analyzed in this paper.

According to [9, 10], the use of geopolymeric materials (high alumina and silica contents) favours reducing CO_2 emissions by 73 % and at the same time, the required energy consumption is reduced by 43 % compared to the use of Portland cement as a binder in the concrete manufacturing.

The development of a very effective process in ecological terms based on turning alumino-silicate materials (waste or natural) in alkaline solution activator into geopolymeric materials with excellent physical-mechanical characteristics was achieved at the end of the 20th century through remarkable invention of the French researcher J. Davidovits [11]. He has identified the geopolymerization reaction of alumina and silica-rich materials into an alkaline solution of sodium or potassium silicate and hydroxide [11, 12]. The curing process of geopolymer concrete can be carried out, according to the inventor J. Davidovits, at ambient temperature or at high temperature. The geopolymerization process is favoured by increasing the temperature, leading to the significant improvement of mechanical strength properties in a much lower time range compared to hardening at ambient temperature [12].

In the work [13], several versions for preparing geopolymer concrete by curing at ambient temperature were experimented using Taguchi method as a quality control procedure aiming at reducing final product failures. Ground granulated blast furnace slag was utilized with the role of alumino-silicate binder. The alkaline activator was a liquid solution composed of sodium silicate and sodium hydroxide in the ratio 2.5, in which the molar concentration of NaOH was 14M. After 7 days to the increase of setting time (and therefore of workability) affected by the use of blast furnace slag, but the compression strength value decreased due to reducing the mixture calcium content of concrete storage, the highest compression strength (60.4 MPa) was obtained. The partially replacing the slag with variable ratios of fly ash, metakaolin, and silica fume, respectively, has contributed.

Fly ash and ground granulated blast furnace slag (added in ratios up to 20 % of the entire binder amount) were alumino-silicate wastes used in the experiment presented in [14]. The alkaline activator was a liquid solution including Na_2SiO_3 and NaOH, the activator/binder ratio being kept constant at 0.35. The curing process was performed at room temperature. The results showed that the compression strength of geopolymer concrete increased from the early age. The increase of the slag amount added to the starting mixture has also contributed to the increase of the concrete mechanical strength. Drying shrinkage, void volume, and sorption had almost similar values to concrete specimens made with Portland cement. Comparing the results of the geopolymer concrete with those of the reference concrete based on Portland cement, the authors showed that the fly ash-slag combination and curing at ambient temperature ensure the durability of the new material at a similar level to that of the reference concrete.

A research team including authors of the current paper previously conducted tests aiming at the production of geopolymer concrete using fly ash and blast furnace slag as binders, activated in Na_2SiO_3 and NaOH solution [15]. The paper originality was the increase of slag ratio range (15-25 %) in the binder mixture, for increasing the compression strength despite the decrease in workability. The fresh geopolymer obtained by mixing the raw material components and pouring into a mold was cured with hot air at 80 °C. After 7 days, the compression strength reached 55.2 MPa corresponding to 25 % slag ratio in the binder amount, but the workability test decreased from 70 to 45 mm. The adopted optimal version was that with 80 % fly ash and 20 % slag. The compression strength for this version reached 53.3 MPa and the fresh concrete workability was 58 mm (corresponding to a medium workability value).

Special interest was given by Hamidi et al. [16] on the concentration of the NaOH aqueous solution as a component of the alkaline activator. Its influence on the mechanical resistance of concrete, especially on the flexural strength, was experimentally determined in the work mentioned above. Under the conditions of using fly ash as the main alumino-silicate binder in the concrete manufacturing process, the optimal concentration of NaOH was determined to be 12M. The curing process of the fresh mixture was performed at 60 °C for 1 day.

The temperature and duration of the curing process of the fresh geopolymer as well as the concentration of the NaOH solution were identified in the work [17] as having significant effects on the compression strength value. Increasing the mentioned parameters led to improving the compression resistance. On the other hand, increasing the water/geopolymer ratio led to the reduction of compression strength value. The role of the superplasticizer based on naphthalene on increasing the workability of fresh concrete was also determined.

The influence of the main known curing techniques of geopolymer concrete (with steam, hot air, and at room temperature) on its mechanical characteristics were analyzed in the paper [18]. The composition of the material mixture included low calcium fly ash, ground blast furnace slag, sand as the fine aggregate, coarse aggregate (below 20 mm particle size), and alkaline activator solution containing Na_2SiO_3 and NaOH mixture. The fly ash amount varied between 392.4-436 $kg \cdot m^{-3}$, while the slag amount had values in the range 0-43.6 $kg \cdot m^{-3}$. The Na_2SiO_3/NaOH ratio was 2.5. The hot air curing method allowed to reach the highest level of compression strength (24.5-28.3 MPa). The curing at ambient temperature reached the highest compression strength after 12 days compared to its value after 3 days, registering maximum 25.5 MPa.

According to the results obtained in the own previous tests [15] as well as those of other authors [17], the increase in the mechanical strength of geopolymer concrete has as a secondary effect the decrease of workability properties. This worsening of the fresh material-flow characteristics can be counteracted by using an adequate fluidizing additive. The authors of the paper [17] chose naphthalene-based superplasticizer suitable for high-strength, steam cured, fluid, waterproof, plasticized or reinforced concretes, being manufactured in China [19].

The authors of the current paper adopted a calcium lignosulfonate (LSC) fluidizing additive, extracted from the sulphite lye resulting from the manufacture of cellulose as a by-product. This type of additive is a polymer with a high molecular mass and a three-dimensional structure. Although LSC was intended to improve the properties of mortars and cement-based Portland concretes, its use was also extended to new geopolymers, considering the similarity of alumino-silicate materials with pozzolanic properties used as substitutes for cement and the ordinary Portland cement in the composition of traditional concrete. According to [20], in general, fluidizing additives contribute to the slight increase of apparent density due to the improvement of workability and the reduction of the working water requirement. Also, the mechanical strength of concrete is increased, allowing the reduction of the dosage of cementitious materials replacing the cement. The improvement of concrete strength after 7 and 28 days can increase by 10-20 % compared to concrete without fluidizing additive. According to the same reference, the presence of fluidizing additives could improve slow flow, especially at early ages. Capillary sorption and concrete permeability are reduced due to the presence of fluidizing additives as a result of reducing the water requirement and increasing the structural homogeneity. The resistance to corrosive attack should be improved as a result of the decrease in permeability.

2. Materials and methods

The solids adopted in this experiment as materials for preparing mixtures for producing the geopolymer concrete were: fly ash, granulated blast furnace, both as binders from residual alumino-silicate materials, Na_2SiO_3 and NaOH in aqueous solution constituting the alkaline activator, sand as fine aggregate, gravel as coarse aggregate, and calcium lignosulfonate as a fluidizing additive.

Coal fly ash, a well-known by-product of the coal burning process in thermal power plant boilers, trapped after the purification of residual gases in electrofilters, was previously supplied by Paroseni-Thermal Power Station and preserved. Having the initial size of particles below 200 µm, it was ground in a ball mill and selected after sieving to sizes below 80 µm.

Granulated blast furnace slag in the form of 2-6 mm-granules was supplied by ArcelorMittal Galati (Romania) over 25 years ago being preserved and used in several experiments. The fine grinding process of the slag allowed to obtain a powder with dimensions less than 100 µm.

Chemical composition of coal fly ash and granulated blast furnace slag was determined in the Romanian Metallurgical Research Institute and are shown in Table 1.

Table 1

Chemical composition of fly ash and blast furnace slag

Composition	Coal fly ash (%)	Blast furnace slag (%)
SiO_2	48.1	36.4
Al_2O_3	26.4	11.6
CaO	3.6	41.8
MgO	3.2	5.8
MnO	-	0.6
Fe_2O_3	8.6	0.8
Na_2O	6.0	0.3
K_2O	4.1	0.4

Sodium silicate (Na_2SiO_3), known as water glass, is soluble in water creating an alkaline solution. In general, it is used as a binder and can contribute to improving the mechanical resistance of ceramic and composite materials [21]. Commercially, it is available in the form of liquid solution with concentrations around 40 %.

Sodium hydroxide (NaOH), known as caustic soda, contains 16.4 % Na_2O, 34.3 % SiO_2, and 49.3 % H_2O. It exists in solid state and is a very water-soluble material. Commercially, it is available in pellet form (with high purity of 98 %). Together with water glass, it forms an excellent alkaline activator [22] also used in this experiment.

Quartz sand (with the density of 1430 $kg \cdot m^{-3}$) was chosen as fine aggregate, having dimensions less than 1.7 mm selected by sieving.

The coarse aggregate was constituted using natural gravel with the density of about 2800 $kg \cdot m^{-3}$. The maximum size of this aggregate was limited to 20 mm.

Calcium lignosulfonate (LSC) as a fluidizing additive was already mentioned above, its main role being to improve the fresh material-flow features. Generally, calcium lignosulfonate is available in the form of a fine powder (average density of 1200 $kg \cdot m^{-3}$), soluble in ordinary water. The authors' team benefited from a batch of this type of additive previously procured from the Romanian chemical industry.

Unlike the first article of the authors' team from 2022 [15], in the current paper some important changes were made in the starting composition of mixture for manufacturing the geopolymer concrete. Keeping constant the total amount of the alumino-silicate binder (substitute for Portland cement), the weight ratio of fly ash and granulated blast furnace slag was changed, using the following ranges of values: 77-83 wt. % for fly ash and 17-23 wt. % for slag. Na_2SiO_3 and 12M NaOH were the components of the alkaline activator. The weight ratio between the activator and the alumino-silicate binder was adopted at a constant value of 0.358. According to the literature [23], the water addition into the binder mixture is important. A low value of the water/geopolymer binder ratio (0.25 wt. %) leads to obtaining a very viscous and stiff mixture, therefore with inadequate workability, but ensures excellent mechanical strength of the concrete. By increasing the water/binder ratio, the workability of the fresh material improves, but the compression strength decreases. Experimentally, the ratio of 0.28 was adopted, meaning an added water amount of 126 $kg \cdot m^{-3}$. Unlike the reference work [15], the main novelty of the mixture composition for the acceptable correlation of the two features of geopolymer concrete (strength and workability) was the addition of calcium lignosulfonate (LSC) as a fluidizing additive. According to [24], its weight proportion must be below 1 wt. % of the binder amount, the paper referring to the traditional concrete binder, i.e. the Portland cement. From the authors' own experience, a maximum value of 0.31 wt. % is more advisable in the case of geopolymer concrete, meaning an additive amount of 1.4 $kg \cdot m^{-3}$. The two types of aggregate chosen in this experiment (quartz sand as fine aggregate and natural gravel as coarse aggregate) had the usual role in any type of concrete, including geopolymer concrete [25]. The weight ratio between the entire amount of aggregate and the alumino-silicate binder was adopted at the value of 4.8. The binder amount being 450 $kg \cdot m^{-3}$, it results that the total aggregate was 2160 $kg \cdot m^{-3}$. Choosing the weight proportion of 35 % for fine aggregate and 65 % for coarse aggregate respectively, the corresponding amounts of the two types of aggregate were determined: 756 kg·m^{-3} (quartz sand) and 1404 kg·m^{-3} (coarse aggregate).

The experiment presented below contains four experimental versions marked V1-V4 (Table 2), in which the amounts of fly ash and granulated blast furnace slag ratio is reduced from 4.88 (V1) to 3.35 (V4), the other values of mixture component amounts being kept constant.

Table 2

Composition of experimental versions of geopolymer concrete

Composition	V1 (kg·m^{-3})	V2 (kg·m^{-3})	V3 (kg·m^{-3})	V4 (kg·m^{-3})
Fly ash	373.5	364.5	355.5	346.5
Granulated blast furnace slag	76.5	85.5	94.5	103.5
12M NaOH	46	46	46	46
Na_2SiO_3	115	115	115	115
Quartz sand	756	756	756	756
Coarse aggregate	1404	1404	1404	1404
Supplementary water added	126	126	126	126
Calcium lignosulfonate	1.4	1.4	1.4	1.4

The conversion of alumino-silicate materials (mostly industrial waste such as coal fly ash, metallurgical slag, red mud, rice husk ash, etc.) into products with special mechanical and physical characteristics called geopolymers, as a result of developing the geopolymerization reaction activated by an alkaline activator, constitute the basic elements of the remarkable invention of the French researcher J. Davidovits mentioned above. Alumino-silicate materials have pozzolanic properties having ability to replace the traditional Portland cement as a binder in geopolymer concrete manufacturing.

The geopolymerization process is based on a complex chemical reaction between an alkali solution and the alumino-silicate material and forms a three-dimensional polymeric chain and ring structure of Si–O–Al–O bonds. The reaction, that can occur at ambient temperature, is developed in three main stages: dissolution of alumino-silicate material into aluminates and silicates species, condensation of monomers (when the setting time is beginning), and the monomer polymerization into an amorphous inorganic polymer [26].

The adopted working method has included firstly preparing the alkaline activator mixture containing sodium silicate solution (Na_2SiO_3) and water-soluble NaOH pellets dissolved in distilled water (with 12M molarity). The activator homogenization was performed by mechanical stirring in a quartz vessel for 3 min. Separately, the preparation of the solid mixture was carried out in another vessel. First, the mixture containing ground fly ash, ground granulated blast furnace slag, and calcium lignosulfonate was mechanically mixed for 5 min and then fine sand (below

1.7 mm), coarse aggregate (below 20 mm), and supplementary water were introduced over the first solid mixture. After the homogenization of the two solid mixtures for 3 min, the alkaline activator was poured over these. A last mixing together of the solid and liquid materials was performed for about 5 min, until a paste was obtained. The paste, representing fresh geopolymer concrete, was poured into cubic and rectangular molds, placed in a thermally insulated enclosure and heated with hot air at 80 ℃ from an electric air preheater. The duration of the curing treatment of the fresh geopolymer was 24 hours. The characteristic peculiarities analysis of the hardened geopolymer concrete was performed after 7 and 28 days of storage of specimens removed from the molds.

Characterization methods of geopolymer concrete specimens were the following. The fresh geopolymer concrete workability was analyzed according to ASTM C 143-10, Standard for concrete slump test, with the slump test apparatus. Water-absorbing was determined by the immersion method of specimen under water (ASTM D570) after its storage for 28 days [27]. The geopolymer concrete density was measured by Archimedes' method by the water intrusion technique (ASTM D792-20). The compression strength was identified with 100 kN-compression fixture Wyoming Test Fixture [28] and the flexural strength was measured by carrying out the three-point bend test on the specimen (SR EN ISO 14125: 2000). The microstructural appearance of geopolymer concrete specimens was examined with the Biological Microscope model MT5000 with image captured with a Nikon Coolipix 3 mp Camera, 1000 x magnification.

3. Results and discussion

The workability of fresh geopolymer concrete samples was determined by slump tests and the conclusion was that in the four experimental versions its value significantly changed by increasing the weight ratio of slag in the binder composition, respectively by decreasing the fly ash/slag ratio from 4.88 to 3.35, according to the data in Table 3.

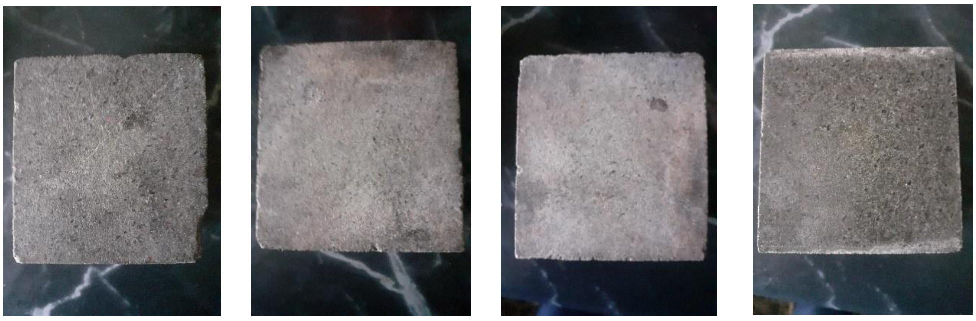
Table 3

Results of the workability test

Experimental version	V1	V2	V3	V4
Fly ash/slag ratio	4.88	4.26	3.76	3.35
Workability slump test (mm)	75 (medium)	69 (medium)	57 (medium)	46 (low)

According to the Standard for concrete slump test (ASTM C 143-10), the first three specimen versions had medium workability (within the limits of 57-75 mm), while the V4 version had low level of workability (46 mm). The mentioned standard delimits the medium level between 50-100 mm and low level in the range of 25-50 mm.

The hardened geopolymer concrete after the curing process at 80 ℃ for 1 day and the storage for 7 and 28 days gained compactness and high mechanical strength, especially after 28 days. The specimens were obtained by pouring the fresh material into cubic shapes with the side dimension of 100 mm (for measuring the compression strength) and rectangular shapes with dimensions of 100 x 100 x 350 mm (for measuring the flexural strength) [29]. The appearance of the cubic specimens made in the four experimental versions is shown in Fig. 1.



V1 V2 V3 V4

Fig. 1. Appearance of the cubic shape specimens
V1 – version 1; V2 – version 2; V3 – version 3; V4 – version 4.

The outer surface appearance of specimens does not visibly differ. However, their physical and mechanical features as well as the microstructural aspects have distinct peculiarities.

The density of geopolymer concrete specimens, measured on cubic shape samples after 28 days-hardening, reached high values within the limits of 2488-2506 $kg \cdot m^{-3}$, the tendency of slight increase in density being noted in the case of reducing the fly ash/slag ratio, i.e. increasing the weight ratio of granulated blast furnace slag in the binder composition from 17 to 23 wt. %. The compression strength of specimens reached very high levels, especially after 28 storage-days of over 50 MPa (between 53.9-59.7 MPa), its increase being the result of blast furnace slag addition together with fly ash in the alumino-silicate binder composition. The flexural strength also reached high values after 28 days between 7.8-12.1 MPa. The tests on the geopolymer concrete water-absorbing capacity showed that the absorption degree was limited to very low water proportions (around 1 wt. %) and practically, the addition of slag along with fly ash did not influence this geopolymer characteristic.

The centralized presentation of the main characteristics of geopolymer concrete samples made in this experiment is carried out in Table 4.

Table 4

Main physical-mechanical features of specimens

Characteristic	V1	V2	V3	V4
Density after 28 days ($kg \cdot m^{-3}$)	2488	2495	2501	2506
Compression strength (MPa)				

Characteristic	V1	V2	V3	V4
- after 7 days - after 28 days	31.8 53.9	32.6 55.4	34.0 57.4	36.1 59.7
Flexural strength (MPa) - after 7 days - after 28 days	 3.8 7.8	 4.9 8.7	 6.6 10.1	 8.0 12.1
Water-absorbing after 28 days (vol. %)	1.1	1.0	0.9	0.9
Workability level (mm)	75 (medium)	69 (medium)	57 (medium)	46 (low)

As stated above, in this experiment the aim was to find the optimal correlation between the mechanical strength of the hardening geopolymer concrete and the fresh geopolymer workability. Analyzing the data in Table 4, authors' team considered that a very good correlation between the two characteristic types was obtained in the experimental version V3. Having a fly ash/slag ratio of 3.76, which includes 79 % fly ash and 21 % granulated blast furnace slag, the workability of the fresh material was determined by slump test at 57 mm, considered as a medium level workability according to the standard. On the other hand, the compression strength reached the maximum value of 57.4 MPa after 28 days, while the strength after 7 days was 34.0 MPa. Also, the flexural strength reached 10.1 MPa after 28 days and 6.6 MPa after 7 days, which means excellent strength values.

The microstructural appearance of geopolymer concrete specimens is shown in Fig. 2.

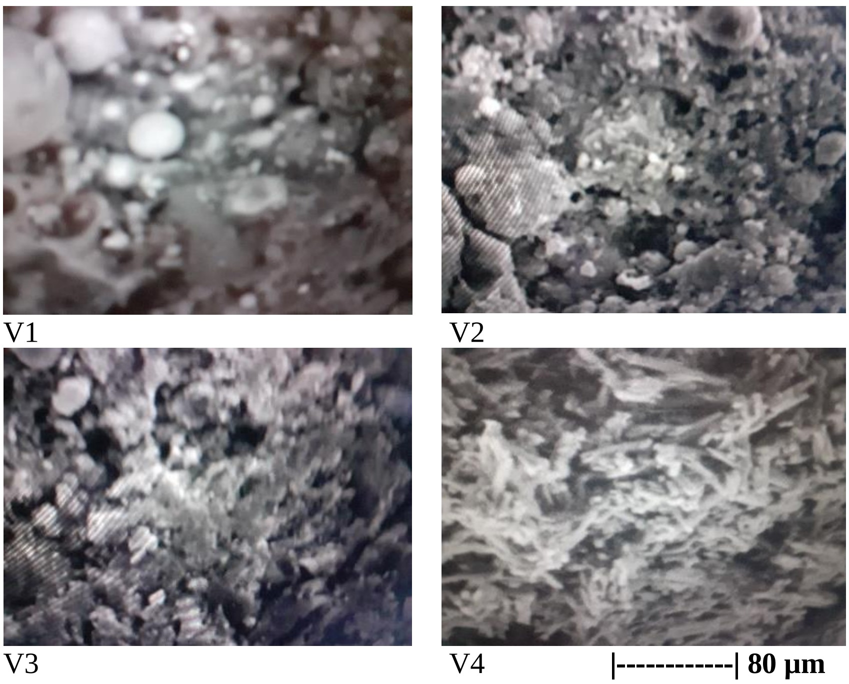


Fig. 2. Microstructural appearance of geopolymer concrete specimens
V1 – version 1; V2 – version 2; V3 – version 3; V4 – version 4.

The pictures in Fig. 2, present the changes at the microstructural level caused by increasing the proportion of ground granulated blast furnace slag in composition of the binder dominated by the fly ash component. The typically spherical grains of ash are clearly predominant in pictures V1 and V2, instead, in picture 4 they almost completely disappear, leaving the place of a typical microstructure for metallurgical slag.

Fly ash is the most important alumino-silicate binder due to its pozzolanic properties, which makes it suitable for replacing the ordinary Portland cement. The manufacture of fly ash-based geopolymer, one of the important ideas of the geopolymer creator (J. Davidovits), imposes as a main condition of the coal fly ash characteristics for contributing to the development of the geopolymerization reaction in alkaline medium, the low content of lime (CaO). Class F-fly ash represents the appropriate group, which includes the ash from burning anthracite (bituminous coal). According to the existing standards, class F contains between 1-10 % CaO, its values as low as possible (below 5 %) being preferable. Fly ash purchased from Paroseni during a period when the Thermal Power Pant was operating with anthracite has in its composition 3.6 % CaO (according to Table 1).

Fly ash with low calcium content after grinding below 80 µm is known as a fine powder with spherical granules having pozzolanic properties quite similar to Portland cement, which it can replace. These properties facilitate the reaction of fly ash, in the presence of water, with calcium hydroxide forming hydrated calcium silicates as well as calcium aluminates. Thus, the liquid phase created in the paste due to the hydration process is saturated with calcium hydroxide, reacting with fly ash in addition to the alkaline salts. The use of fly ash and ground granulated blast furnace slag has an important impact on the properties of concrete (or geopolymer concrete) due to the filling and rheological effects]5].

Due to the viscous peculiarity of the NaOH solution used as an alkaline activator in the manufacture of geopolymer concrete, the geopolymer rheology is quite variable. The slump value of the fresh material decreases by increasing the weight proportion of granulated blast furnace slag and the molarity of NaOH [3].

Because the fly ash reactivity is not suitable to be activated at room temperature by alkaline activators, the temperature of its curing process requires higher temperatures (60-85 °C). Thus, incompletely reacted gels affect the full development of the geopolymerization reaction. Experimentally, it was found that granulated blast furnace slag can improve the characteristics of fly ash-based geopolymer concrete by curing at room temperature probably due to the high content of CaO (over 40 %) in the slag composition [9].

The comparison with other works presented in the literature confirmed the originality of the current work. Few published articles refer to results obtained in the field of geopolymer concrete based on fly ash and granulated blast furnace slag because, although the addition of slag increases the geopolymer mechanical strength, the workability of the fresh material is affected, worsening the practical application conditions. The paper [30] is an example in this sense. The compression and flexural strengths reported in this work are lower than those obtained in the current work. Compared to the reference article [15], published by the same authors' team in 2022, the mechanical performances of the geopolymer concrete were improved firstly, by using a fluidizing additive (calcium lignosulfonate) that allowed obtaining an optimal correlation between strength and workability. In addition, the increased duration of concrete storage up to 28 days allowed obtaining superior mechanical performances compared to the reference article.

4. Conclusions

The objective of the current paper was the production of geopolymer concrete based on two alumino-silicate wastes used as a substitute binder for traditional cement (fly ash and granulated blast furnace slag), in which the slag proportion was over 20 wt. %, which normally negatively affects the workability of the fresh material, but greatly increases the mechanical resistance of the hardened geopolymer. The work originality consisted in finding the optimal correlation between the increase in geopolymer strength due to the decrease of the fly ash/slag ratio and the contribution of the fluidizing additive (calcium lignosulfonate) on increasing the material fluidity to an acceptable medium level. The basic principles of turning alumino-silicate materials into geopolymers with special properties, through the geopolymerization reaction in the presence of the liquid alkaline activator, provided in the remarkable recent invention of the researcher J. Davidovits, were preserved in this experiment. The results showed excellent mechanical performances of the geopolymer concrete obtained as a result of the curing process at 80 ℃ for 1 day, continued by the specimen storage for 7 and 28 days, under the conditions that the level of workability determined by the slump test was acceptable at an average value according to the standard. Thus, very high compression and flexural strengths were obtained (57.4 and 10.1 MPa, respectively, after the storage for 28 days as well as 34.0 and 6.6 MPa after the storage for 7 days). Results were better compared to those of other works from the literature. Although the whole range of inventions related to geopolymer concretes and mortars patented by J. Davidovits in the last three decades have a very comprehensive character, numerous versions of preparing these innovative materials have not yet been experimentally verified, so there is a wide availability for new experiments in the future.

References

[1] L.N. Assi, M. Al-Bazoon, K. Carter, R. Anay, „Geopolymer Concrete Can Be the Solution for Sustainable Infrastructure", Proceedings to the Conference The 13th Annual Inter-University Symposium on Infrastructure Management (AISIM), Indiana-Purdue University, Indianapolis, Indiana, the United States, 2017.

[2] J.X. Peng, L. Huang, Y.B. Zhao, P. Chen, L. Zeng, W. Zheng, „Modelling of Carbon Dioxide Measurement on Cement Plants", Advanced Materials Research, vol. 610-613, pp. 2120-2128, 2012. https://doi.org/10.4028/www.scientific.net/AMR.610-613.2120

[3] M.G. Girish, K.S. Kiran, N. Gopinatha, „Synthesis of Fly-Ash and Slag Based Geopolymer Concrete for Rigid Pavement", Materials Today: Proceedings, vol. 60, Part 1, pp. 46-54, 2022. https://doi.org/10.1016/j.matpr.2021.11.332
[4] M.C.G. Juenger, F. Winnefeld, J.L. Provis, J.H. Ideker, „Advances in Alternative Cementitious Binders", Cement and Concrete Research, Elsevier, vol. 41, no. 12, pp. 1232-1243, 2011. https://doi.org/10.1016/j.cemconres.2010.11.012
[5] Z. Giergiczny, „Fly Ash and Slag", Cement and Concrete Research, Elsevier, vol. 124, 2019. https://doi.org/10.1016/j.cemconres.2019.105826
[6] M. Amin, B.A. Abdelsalam, „Efficiency of Rice Husk Ash and Fly Ash as Reactivity Materials in Sustainable Concrete", Sustainable Environment Research, Springer, vol. 29, no. 30, 2019. https://sustainenvironres.biomedcentral.com/articles/10.1186/s42834-019-0035-2
[7] S. Cheng, Z. Shui, T. Sun, R. Yu, G. Zhang, S. Ding, „Effects of Fly Ash, Blast Furnace Slag and Metakaolin on Mechanical Properties and Durability of Coral Sand Concrete", Applied Clay Science, Elsevier, vol. 141, pp. 111-117, 2017. https://doi.org/10.1016/j.clay.2017.02.026
[8] J. Singh, S. Naval, „Partial Replacement of Cement with Red Mud in Concrete-A Review", Sustainable Environment and Infrastructure, pp. 51-70, Part of the Lecture Notes in Civil Engineering book series (LNCE), vol. 90, 2020.
[9] P. Zhang, Z. Gao, J. Guo, S. Shaowei Hu, Y. Yifeng Ling, „Properties of Fresh and Hardened Fly Ash/Slag Based Geopolymer Concrete: A Review", Journal of Cleaner Production, Elsevier, vol. 270, 2020. https://doi.org/10.1016/j.clepro.2020.122389
[10] C. Meyer, „The Greening of the Concrete Industry", Cement and Concrete Composites, Elsevier, vol. 31, no. 8, pp. 601-605, 2009.
[11] J. Davidovits, M. Davidovits, N. Davidovits, „Process for Obtaining a Geopolymeric Alumino-Silicate and Products thus Obtained", US Patent no. 5342595, 1994.
[12] J. Davidovits, „Geopolymers: Inorganic Polymeric New Materials", Journal of Thermal Analysis and Calorimetry, vol. 37, no. 8, pp. 1633-1656, 1991. https://doi.org/10.1007/BF.01912193
[13] N.S. Muhammad, A. Hadi Nabeel, M. Farhan, M. Neaz Sheikh, „Design of Geopolymer Concrete with GGBFS at Ambient Curing Condition Using Taguchi Method", Construction and Building Materials, vol. 140, pp. 424-431, 2017. https://doi.org/10.1016/j.conbuildmat.2017.02.131
[14] P. Sarathi Deb, P. Kumar Sarker, „Properties of Fly Ash and Slag Blended Geopolymer Concrete Cured at Ambient Temperature", Proceedings to the 7th International Structural Engineering and Constructions Conference (ISEC-7), Honolulu, Hawaii, the United States, June 2013.
[15] L. Paunescu, B.V. Paunescu, E. Volceanov, G. Surugiu, „Geopolymer Concrete-A Suitable Nonconventional Alternative Solution for the Global Reduction of CO_2 Emissions in Manufacturing the Concrete", Nonconventional Technologies Review, vol. 26, no. 4, pp. 25-30, 2022.
[16] R.M. Hamidi, Z. Man, K. Azizi Azizly, „Concentration of NaOH and the Effect on the Properties of Fly Ash Based Geopolymer", Procedia Engineering, Elsevier, vol. 148, pp. 189-193, 2016. https://doi.org/10.1016/j.proeng.2016.568
[17] R.V. Prakash, V.D. Urmil, „Parametric Studies on Compressive Strength of Geopolymer Concrete", Procedia Engineering, Elsevier, vol. 51, pp. 210-219, 2013. https://doi.org/10.1016/j.proeng.2013.01.030
[18] S. Kamaravel, „Development of Various Curing Effect of Nominal Strength Geopolymer Concrete", Journal of Engineering Science and Technology Review, vol. 7, no. 1, pp. 116-119, 2014. https://doi.org/10.25103/jestr.071.19
[19] *** Sodium Naphthalene Sulfonate, Kingsun, China, 2023. https://kingsunchemical.com/sodium-naphthalene-sulfonate-formaldehyde
[20] V. Moldovan, „Aditivi in betoane", Editura Tehnica, Bucuresti, Romania, 1978, pp. 139-157.
[21] A. Ayadi, N. Stiti, F. Benhaoua, K. Boumchedda, Y. Lerari, „Elaboration and Characterization of Foam Glass Based on Cullet with Addition of Soluble Silicates", AFI Conference Proceedings

of the International Conference on Advances in Materials and Processing Technologies, vol. 1315, no. 1, 2011. https://doi.org/10.1063/1.3552401

[22] P. Prochon, Z. Zhao, L. Courard, T. Piotrowski, F. Michel, A. Garbacz, „Influence of Activators on Mechanical Properties of Modified Fly Ash Based Geopolymer Mortars", Materials (Basel), vol. 13, no. 5, 2020. https://doi.org/10.3390/ma13051033

[23] S.V. Patankar, S.S. Jamkar, Y.M. Ghugal, „Effect of Water-to-Geopolymer Binder Ratio on the Production of Fly Ash Based Geopolymer Concrete", International Journal of Advanced Technology in Civil Engineering, vol. 1, no. 4, 2012. https://interscience.in/ijatce/vol1iss4/15

[24] J. Sharma, R. Nisha, „Ligno Sulphonate: An Additive in Concrete", International Journal of Advance Research in Science and Engineering, vol. 6, no. 9, 2017. ISSN: 2319-8354.

[25] B.S. Thomas, J. Yang, A. Bahurudeen, S.N. Chinnu, J.A. Abdalla, R.A. Hawileh, H.M. Hamada, „Geopolymer Concrete Incorporating Recycled Aggregates: A Comprehensive Review", Cleaner Materials, vol. 3, 2022. https://doi.org/10.1016/j.clema.2022.100056

[26] I. Ozer, S. Soyer-Uzun, „Relations between the Structural Characteristics and Compressive Strength in Metakaolin Based Geopolymers with Different Molar Si/Al Ratios", Ceramics International, vol. 41, pp. 10192-10198, 2015. https://doi.org/10.1016/j.ceramint.2015.04.125

[27] A. Mishra, D. Choudhary, N. Jain, M. Kumar, N. Sharda, D. Dutt, „Effect of Concentration of Alkaline Liquid and Curing Time on Strength and Water Absorption of Geopolymer Concrete", Journal of Engineering and Applied Sciences, Asian Research Publishing Network, vol. 3, no. 1, pp. 14-18, 2008, ISSN: 1819-6608.

[28] A.A. Dyg Siti Quraisyah, K. Kartini, M.S. Hamidah, „Water Absorption of Incorporating Sustainable Quarry Dust in Self-Compacting Concrete", 4th International Symposium on Green and Sustainable Technology (ISGST), Kampar, Malaysia, October 3-6, 2021, IOP Conf. Series: Earth Environmental Science, vol. 945, IOP Publishing Ltd., 2021. https://doi.org/10.1088/1755-1315/945/1/012037

[29] S. Kushwah, M. Mudgal, R. Kumar Chouhan, „The Process, Characterization and Mechanical Properties of Fly Ash-Based Solid Form Geopolymer via Mechanical Activation", South African Journal of Chemical Engineering, Elsevier, vol. 38, pp. 104-114, 2021.

[30] J. Li, X. Dang, J. Zhang, P. Yi, Y. Li, „Mechanical Properties of Fly Ash-Slag Based Geopolymer for Repair of Road Subgrade Diseases", Polymers (Basel), MDPI, Basel, Switzerland, vol. 15, no. 2, 2023. https://doi.org/10.3390/polym15020309